Outline

- **Astrophysical context**
  - Physical conditions in the inner regions of YSOs
  - Need for very high angular resolution
  - Principle and observables of IR interferometry
  - YSO science results
- **Inner disk physics**
  - Sizes of circumstellar structures
  - Constraints on disk structure
  - Gas/dust connection
- **Origin of the hydrogen emission lines**
  - Outflowing winds ?
  - Magnetospheres ?
- **Observation of exoplanets in disks**
  - Multiple systems in YSOs: GW Ori
  - Detecting Hot Jupiters with the VLTI
  - Detecting planetary gaps in disks
- **Conclusion**
  - Summary
  - What still to expect from interferometry?
  - My projects for the year
  - Where to find me?

Inner regions of young stellar objects revealed by infrared long-baseline interferometry

Fabien Malbet

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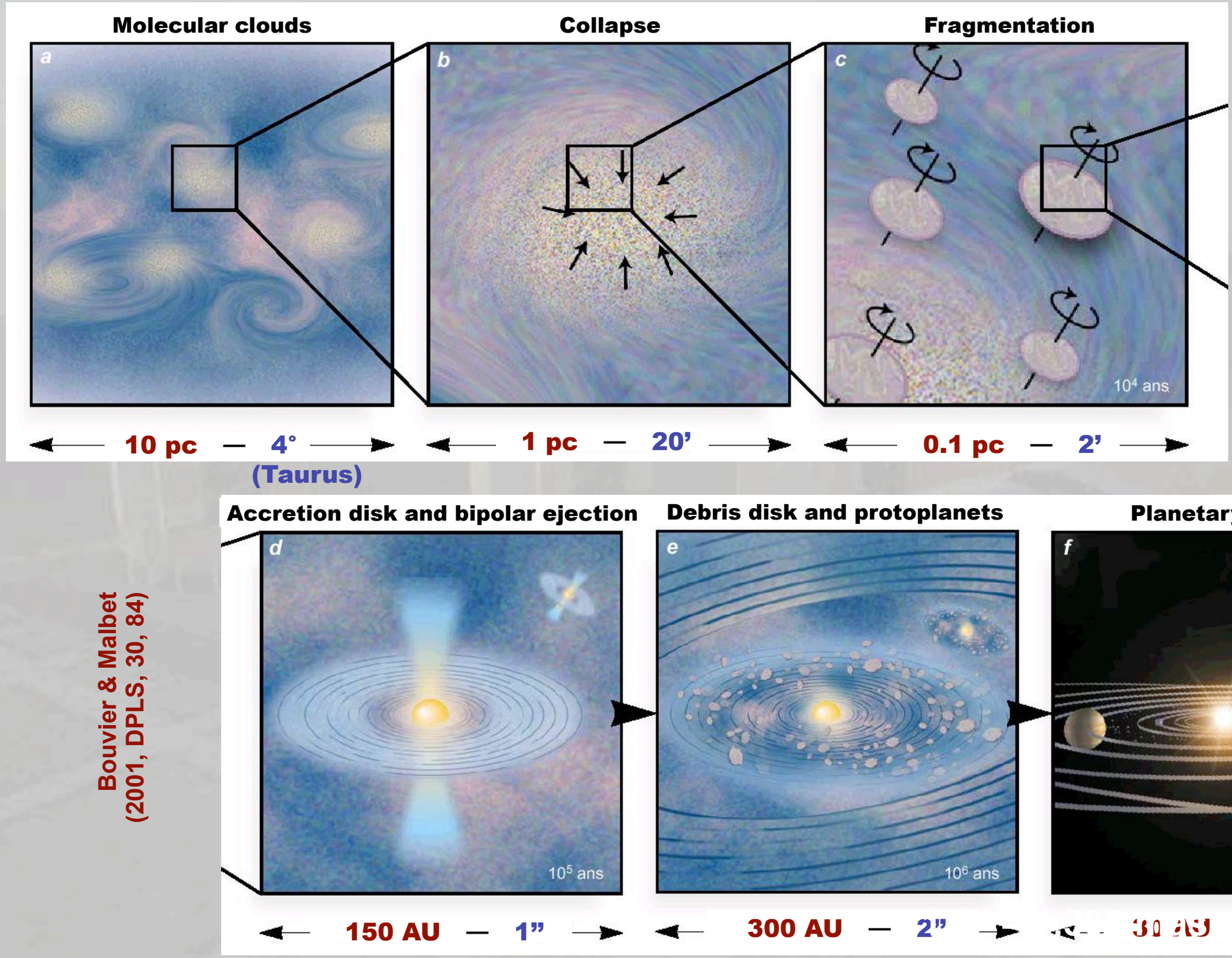
JPL Center for Exoplanet Science Colloquium Series
Pasadena - 18 September 2008

ASTROPHYSICAL CONTEXT

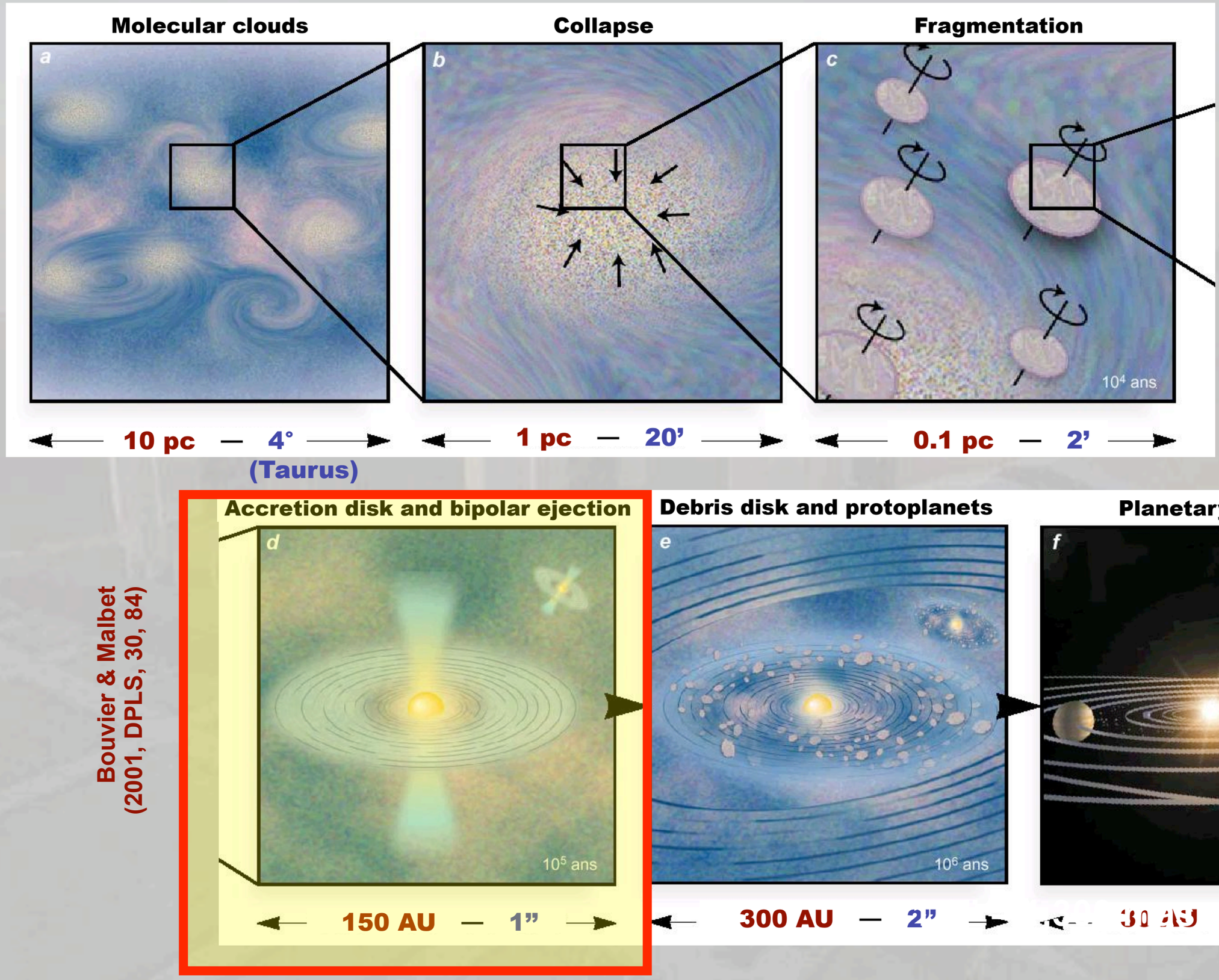
– Physical conditions in the inner regions of YSOs
– Need for very high angular resolution
– Principle and observables of IR interferometry
– YSO science results

Formation of stars, disks and planets

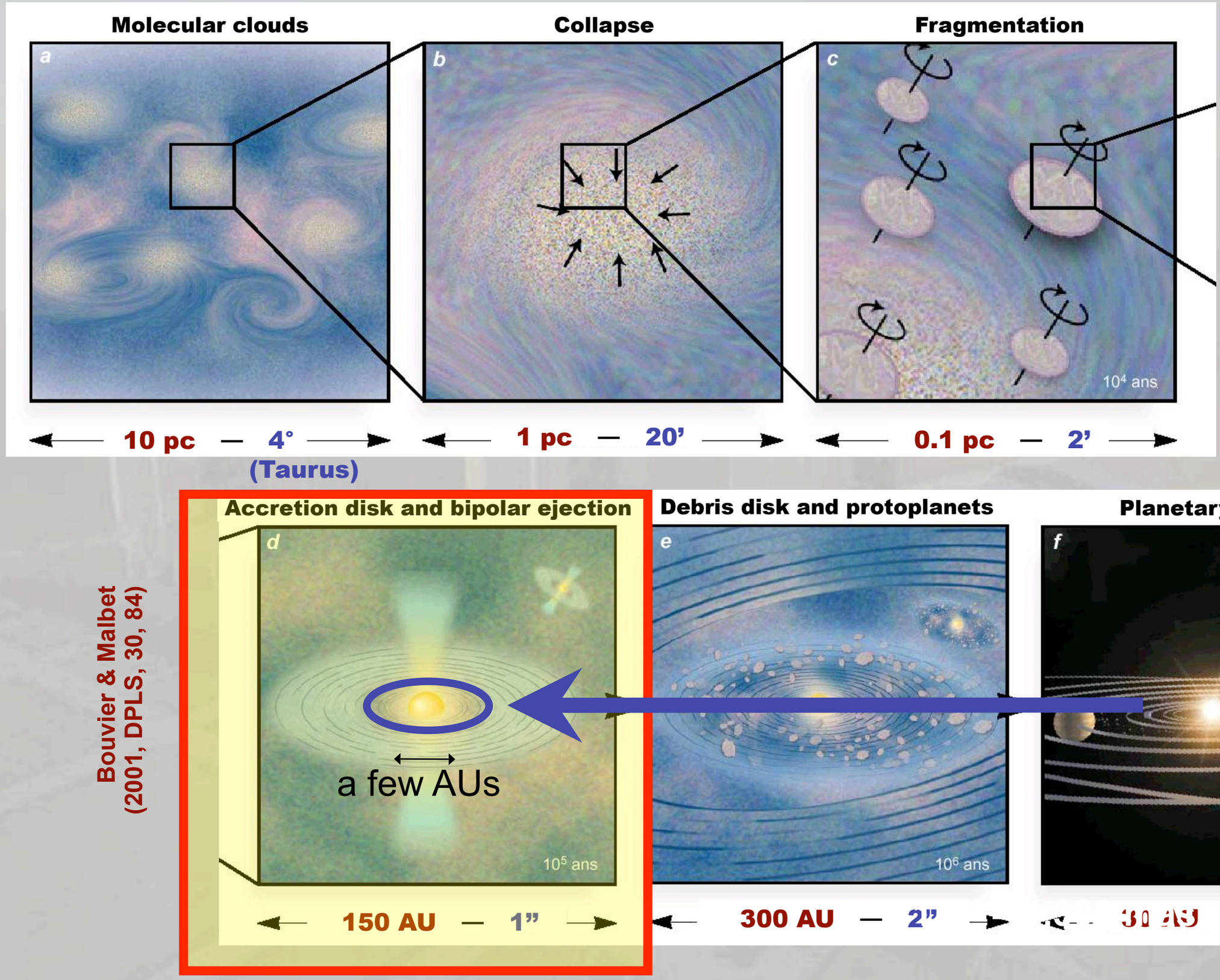


Bouvier & Malbet (2001, DPLS, 30, 84)

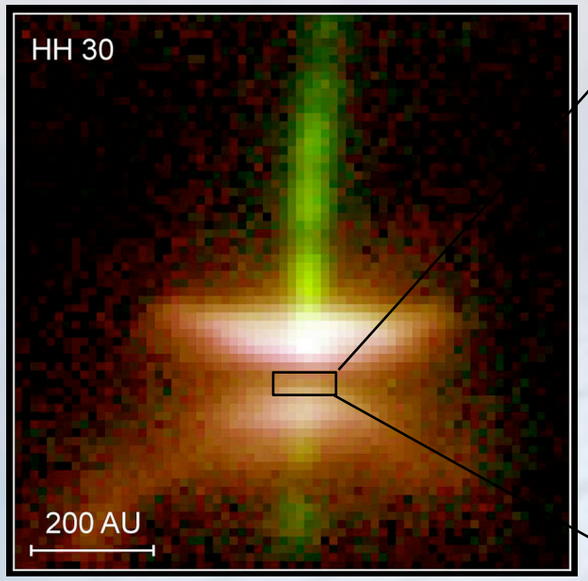
Formation of stars, disks and planets

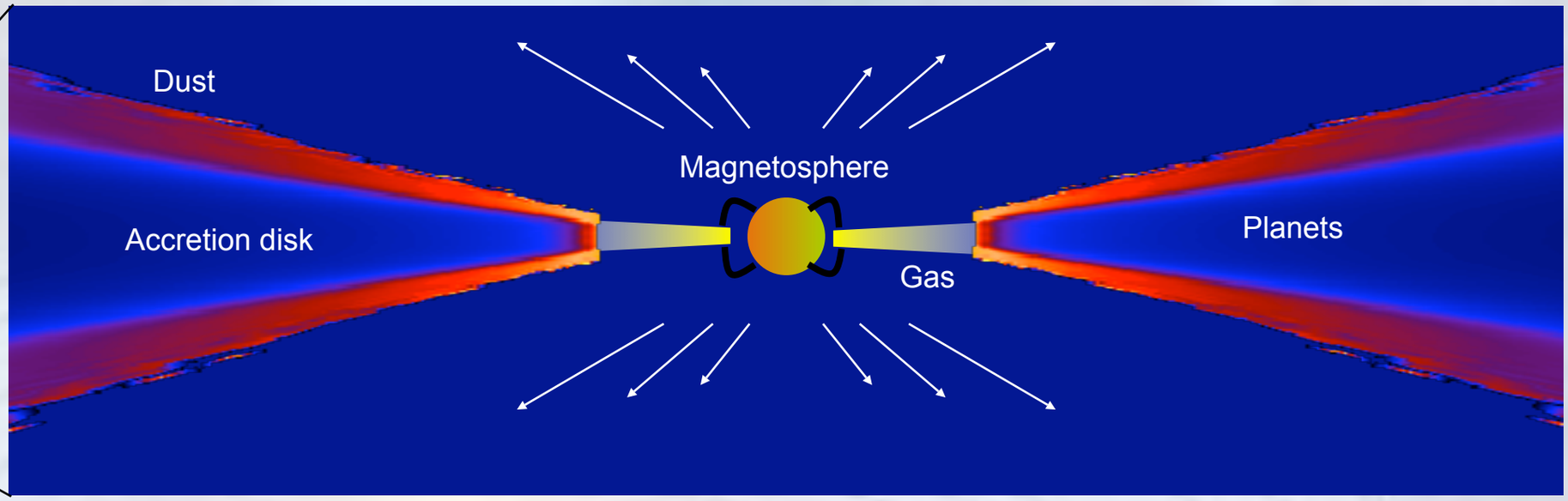


Formation of stars, disks and planets



Physical conditions in the close environment of young stellar objects





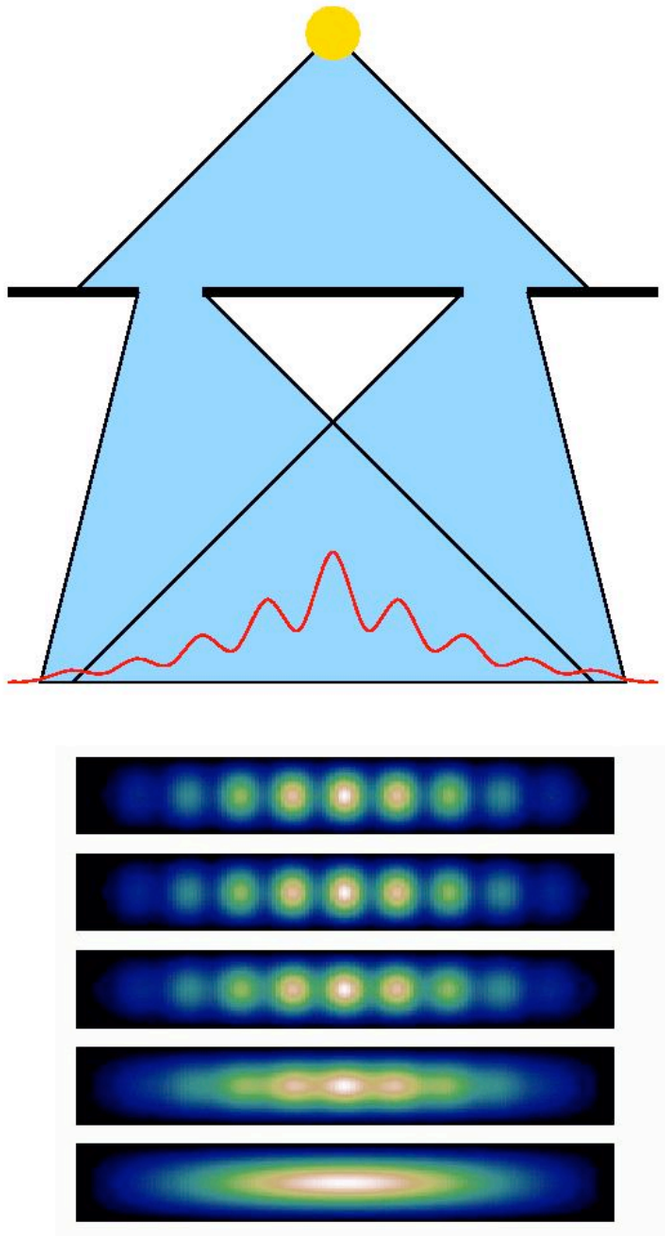
- **Physical phenomena**
  - Keplerian accretion disk: gas + dust
  - Stars from K to B spectral types (4000K to 10000K)
  - Strong outflowing wind
  - Companions
  - Magnetophere
  - Protoplanets

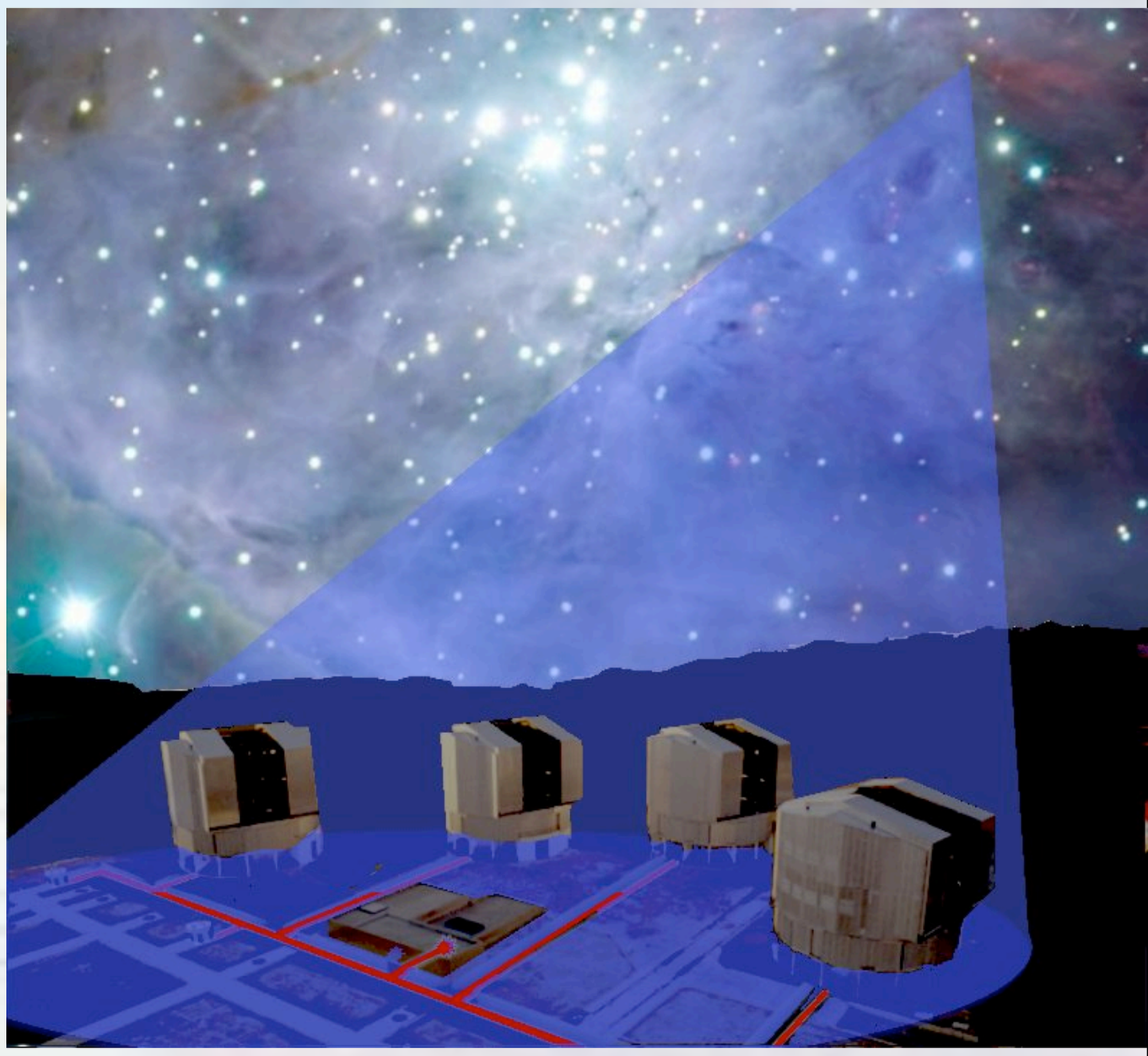
- **Physical conditions**
  - Radius ranging from 0.1 AU to 10 AU
  - Temperature ranging from 150 K to 4000 K
  - Velocity ranging from 10 km/s to few 100 km/s

➡ **At 150 pc (Taurus), this corresponds to :**

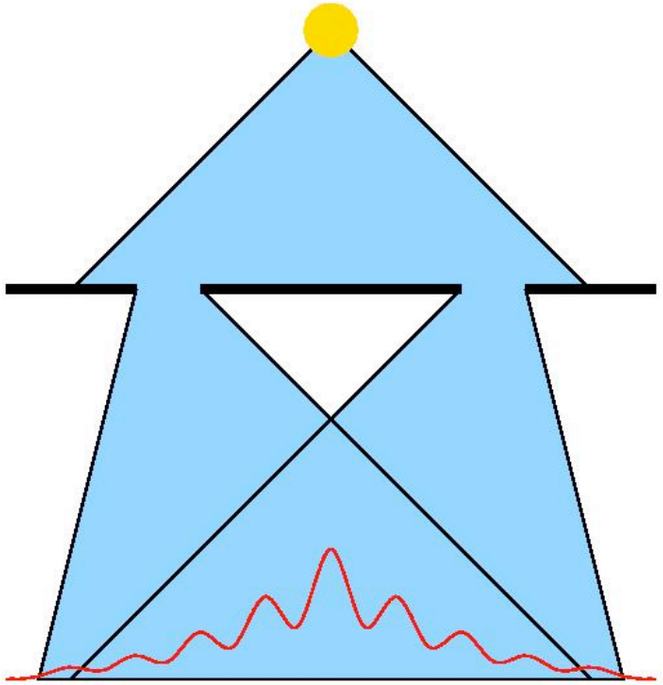
1µm ≤ λ ≤ 20µm and spatial scales between **0.5 et 70 mas**

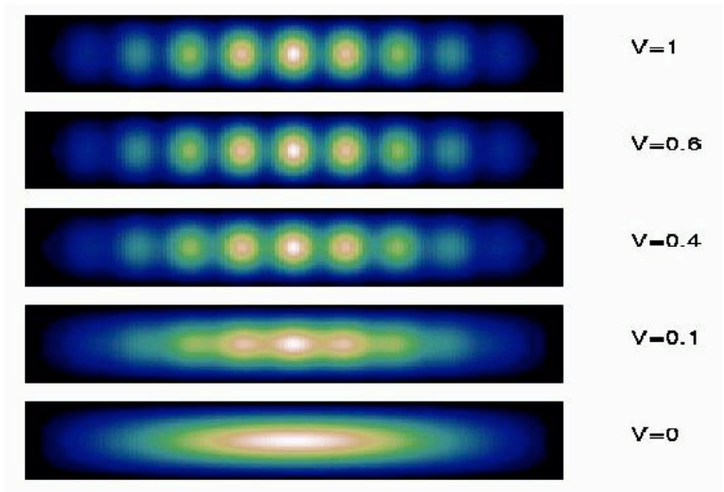
Basics of optical interferometry

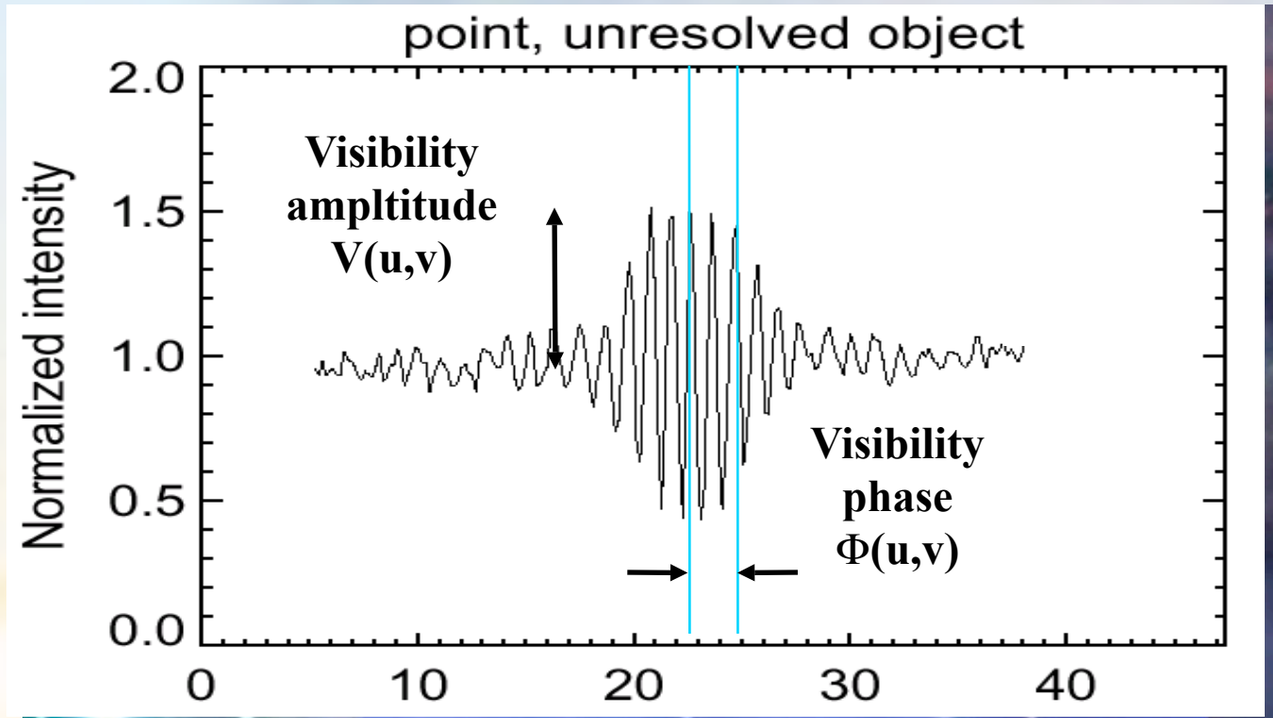


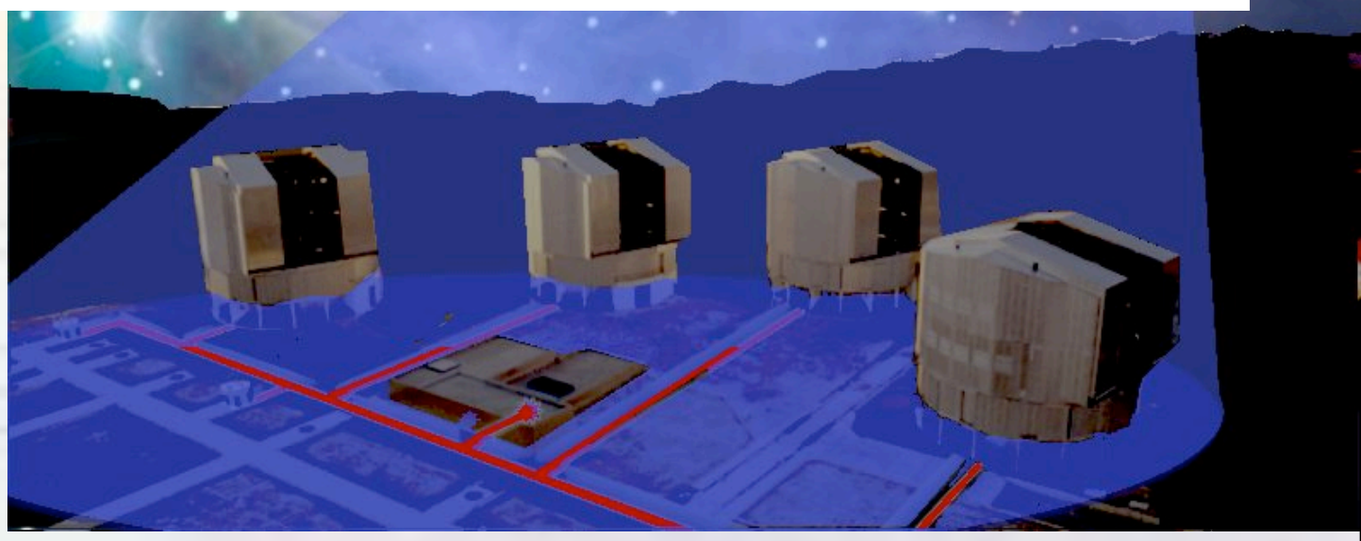


Basics of optical interferometry

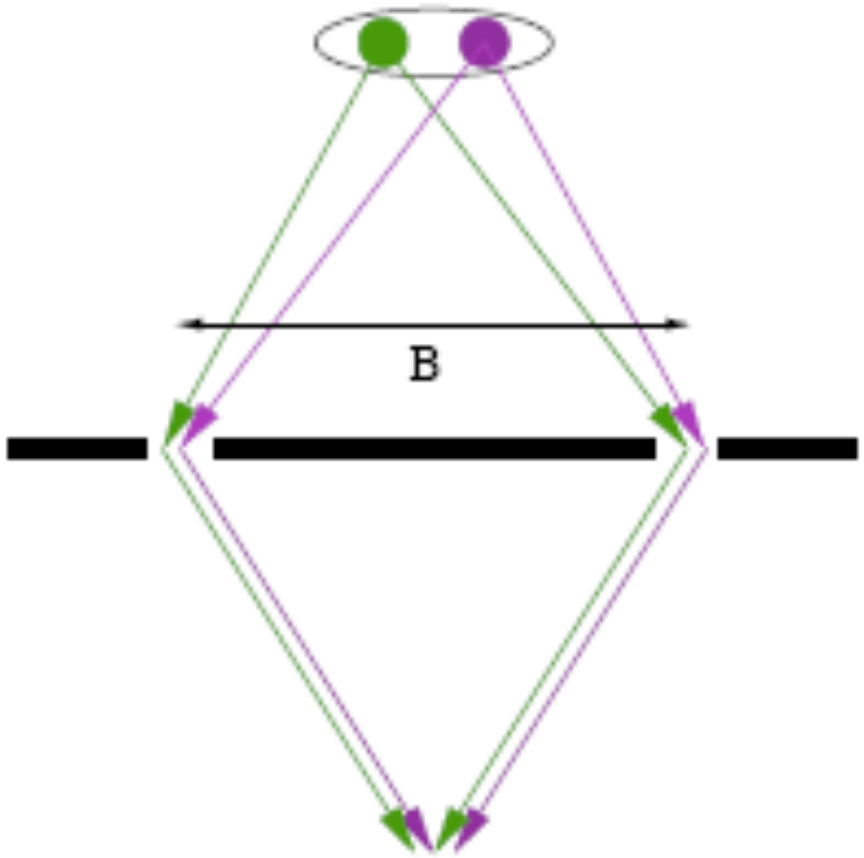


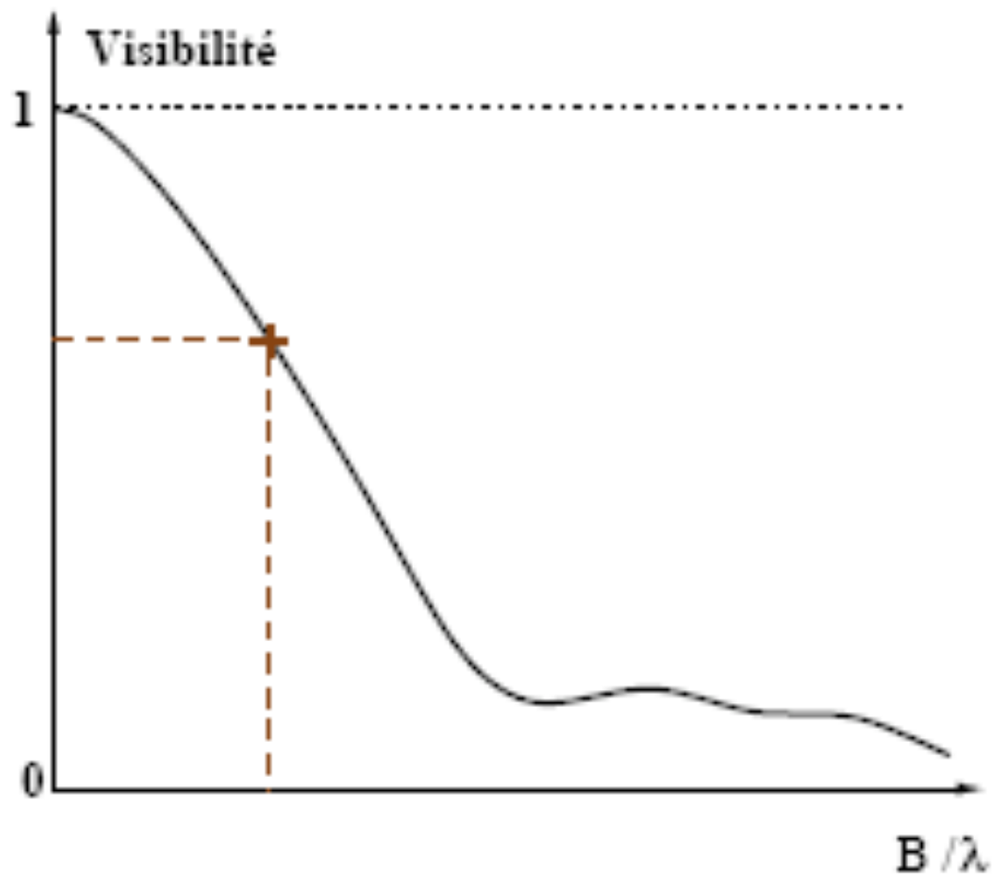






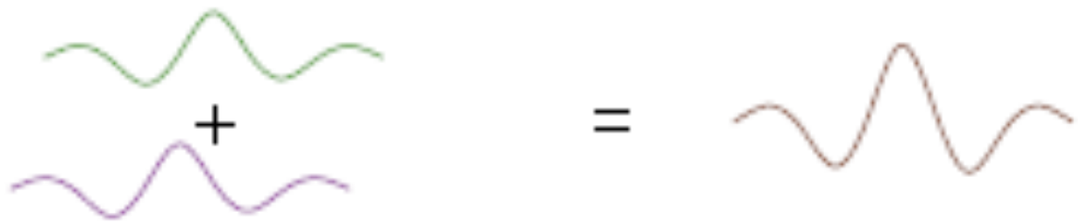
Spatial coherence





Interferogram 1

Interferogram 2

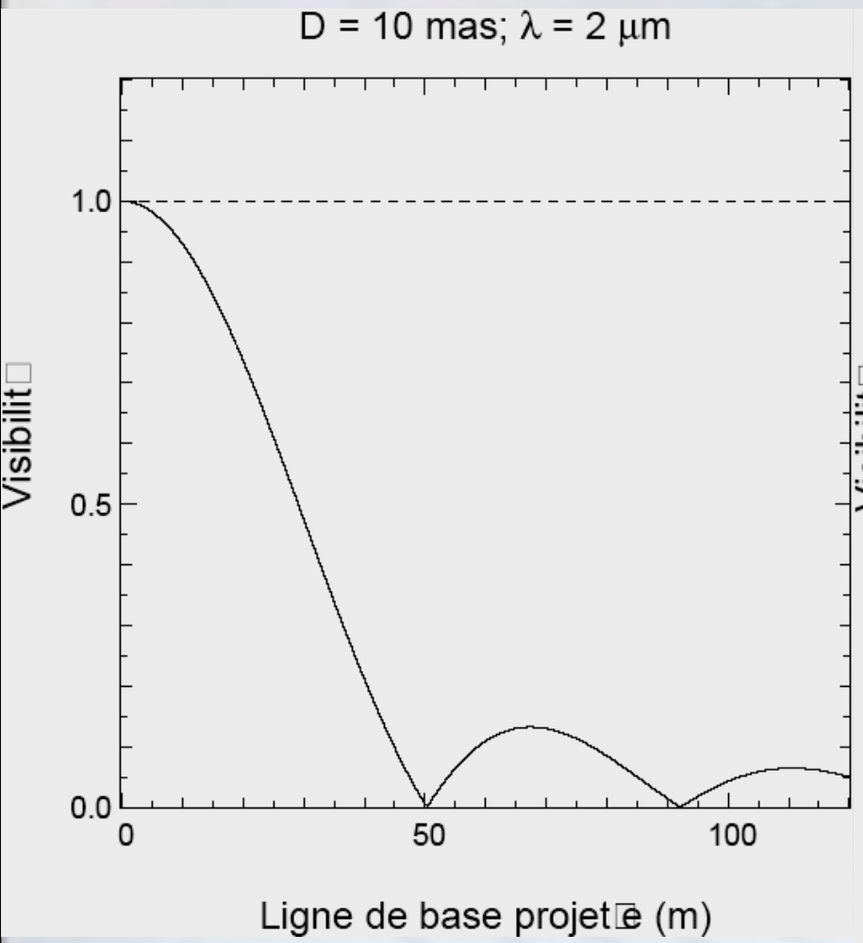


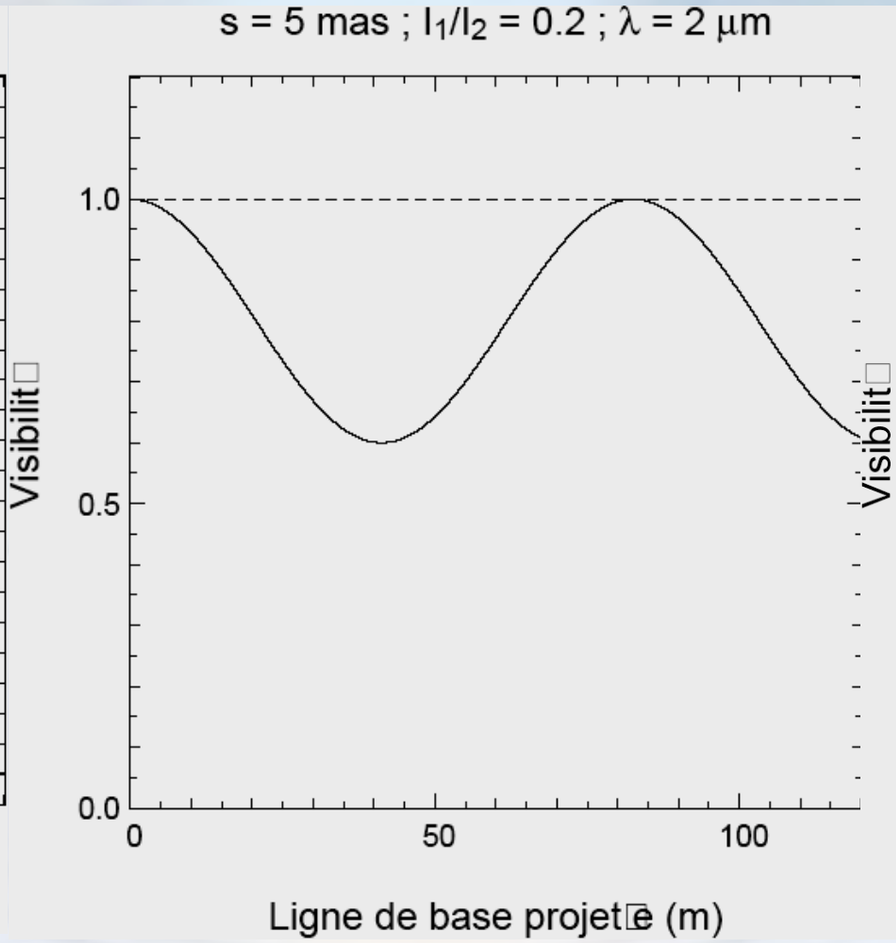
Reduced contrast
Shifted phase

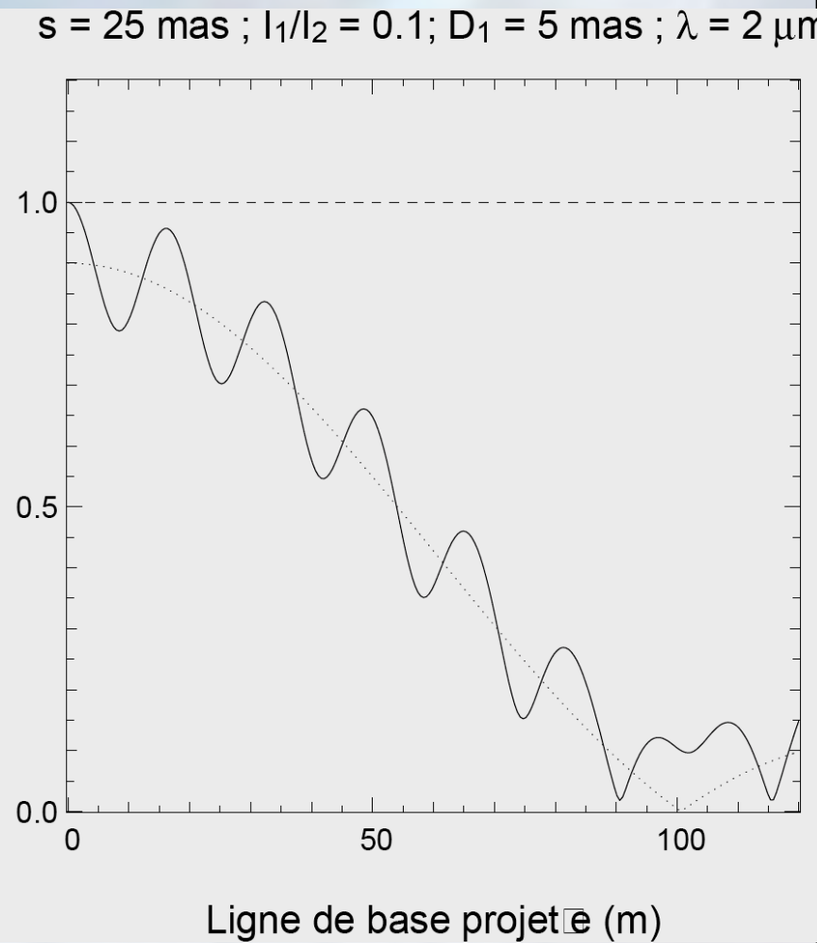
Zernicke-van Cittert theorem

Visibility = Fourier transform of the brightness spatial distribution

Visibilities







Uniform disk

Binary with unresolved components

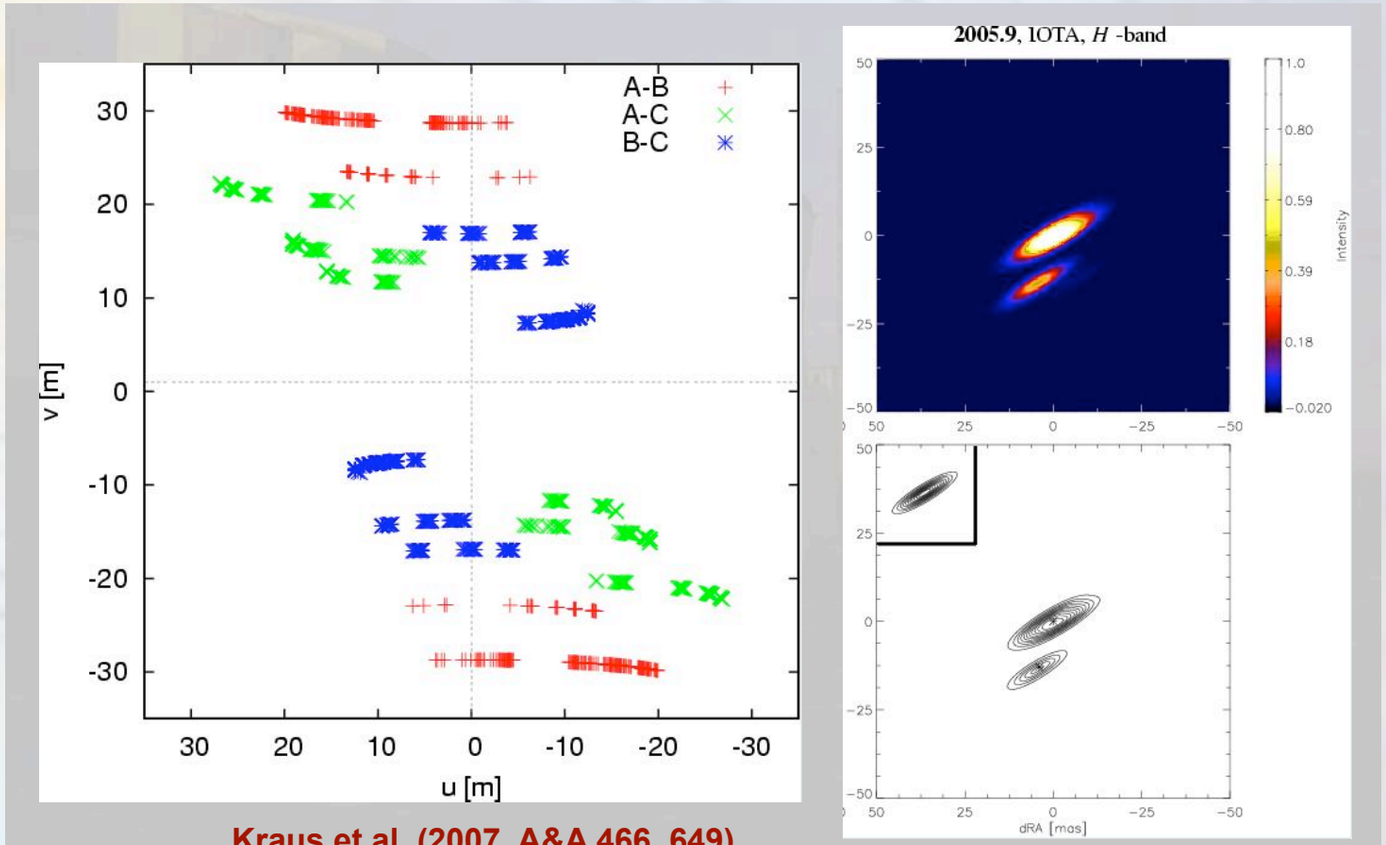
Binary with resolved component

For a resolved source, given a **simple model** (uniform disk, Gaussian, ring,...), there is a **univoque relationship between a visibility amplitude and a size.**
However this size is very dependent on the input model

Image reconstruction

- Like in radio, enough data points permits to reconstruct an image whose FT fits the data
- However in optical we lose a part of the phase signal to the atmosphere
- Optical interferometry arrays have fewer telescopes (<4-6)

BUT starts to be possible: θ^1 Ori C

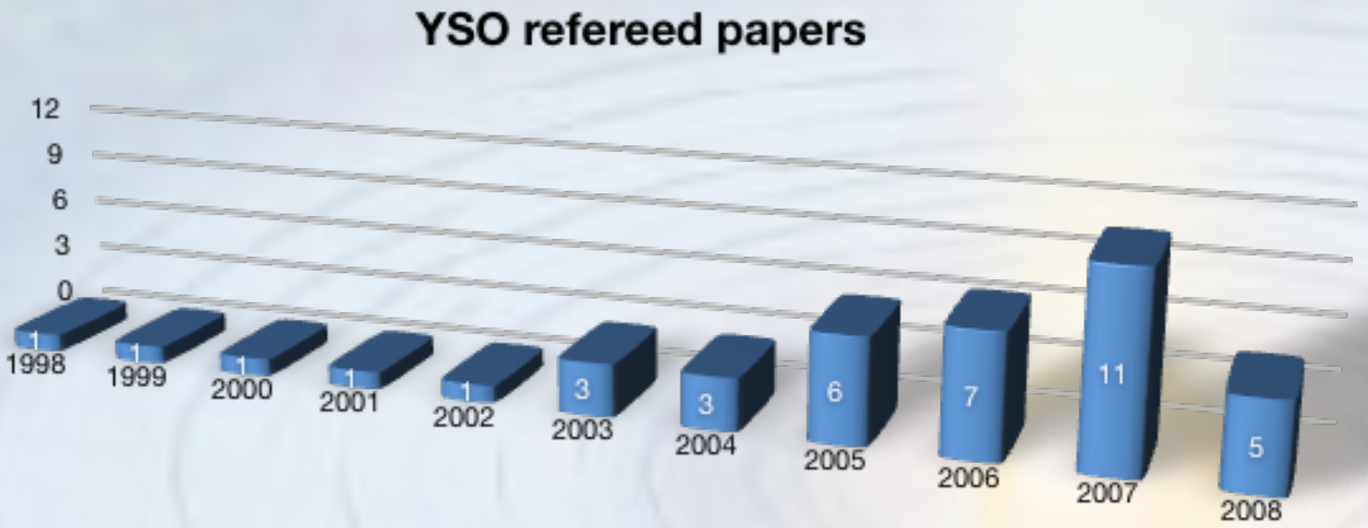


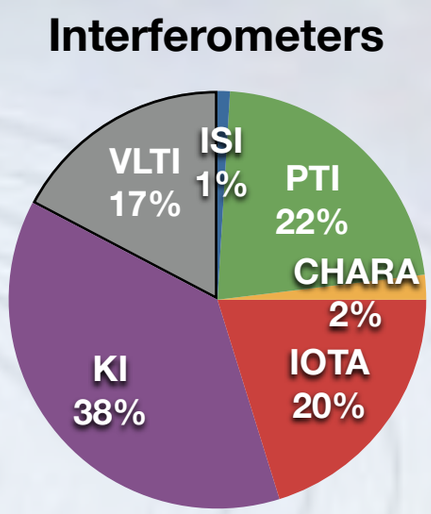
Kraus et al. (2007, A&A 466, 649)

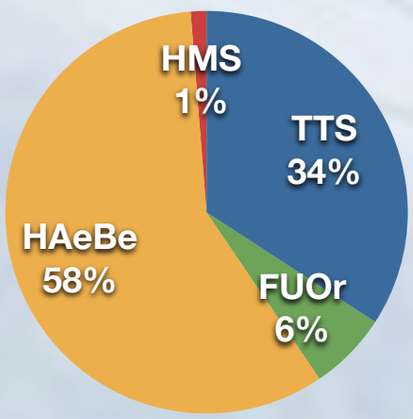
YSOs observed in the last decade (1998-2008)

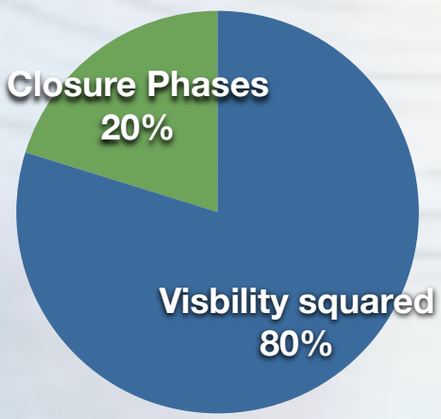
→ **79 young stellar objects** observed and published to date,

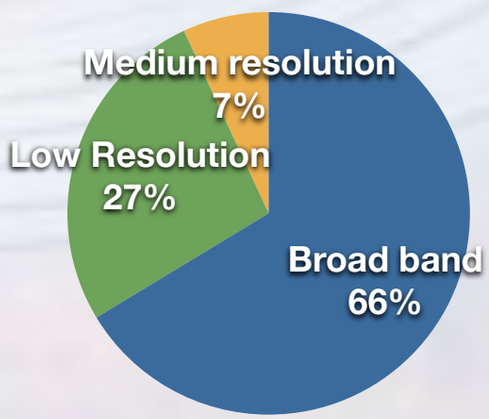
→ **40 refereed articles**

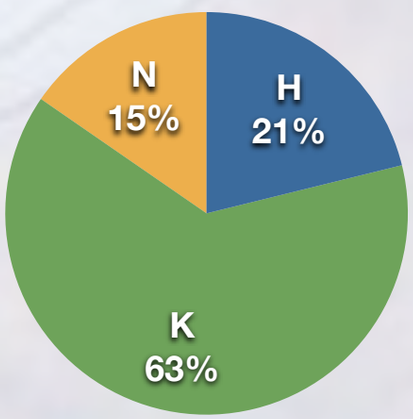








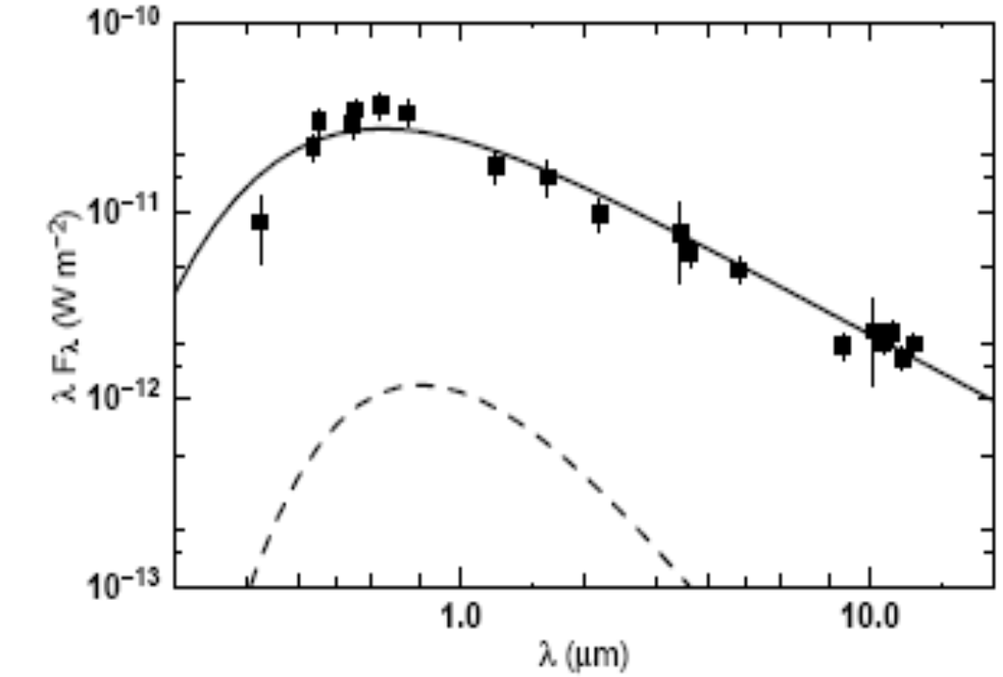


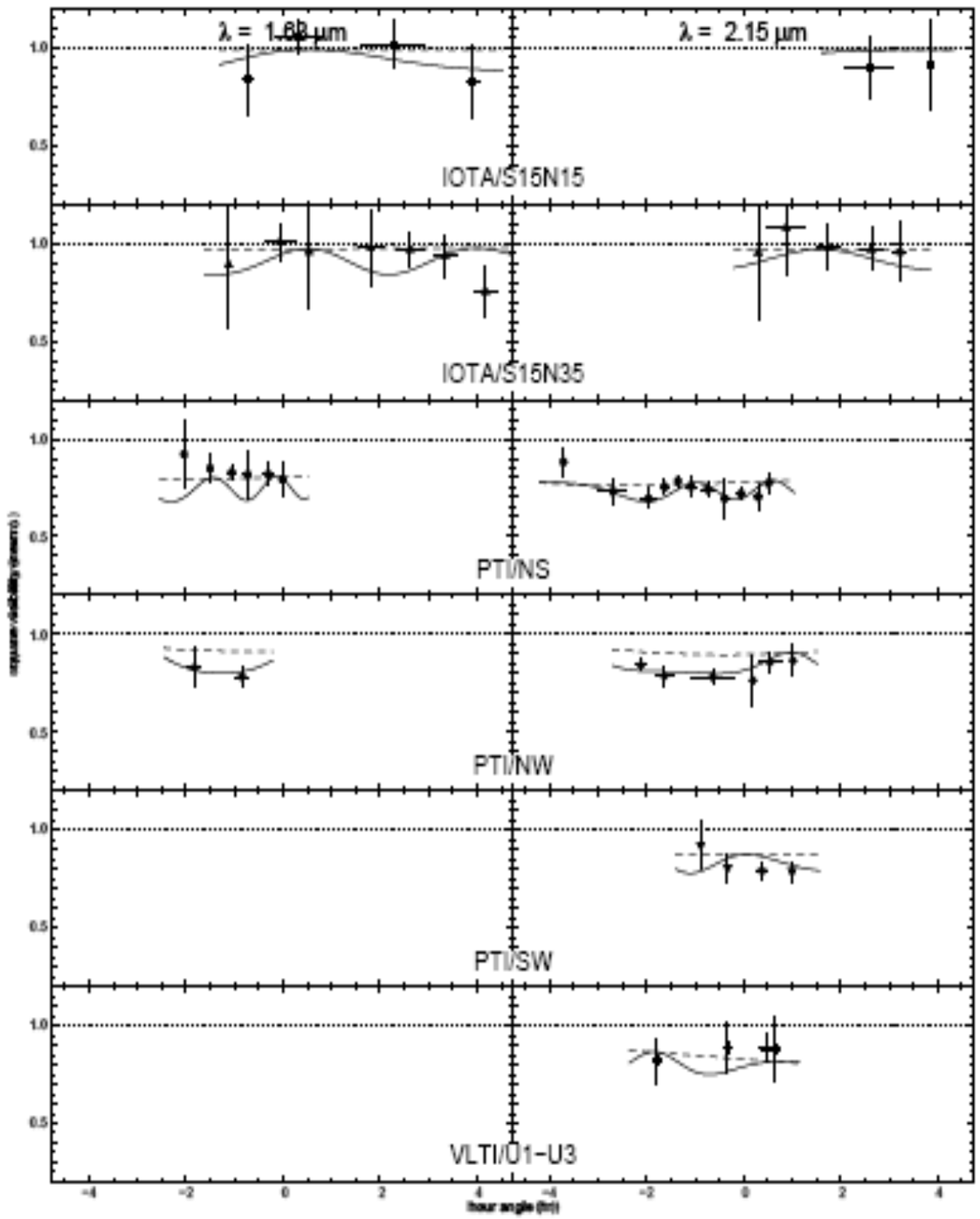


INNER DISK PHYSICS

– Sizes of circumstellar structures
– Constraints on disk structure
– Gas/dust connection

FU Orionis

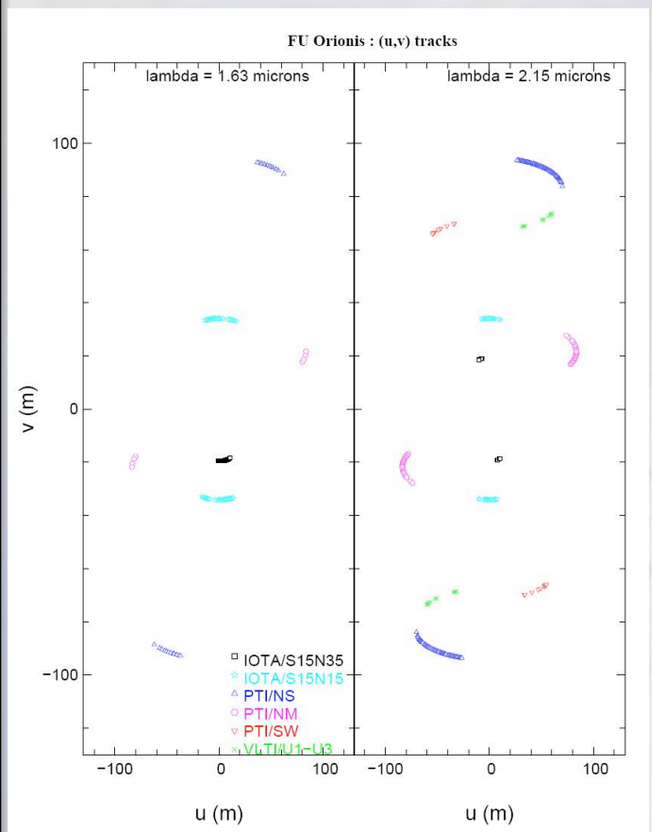


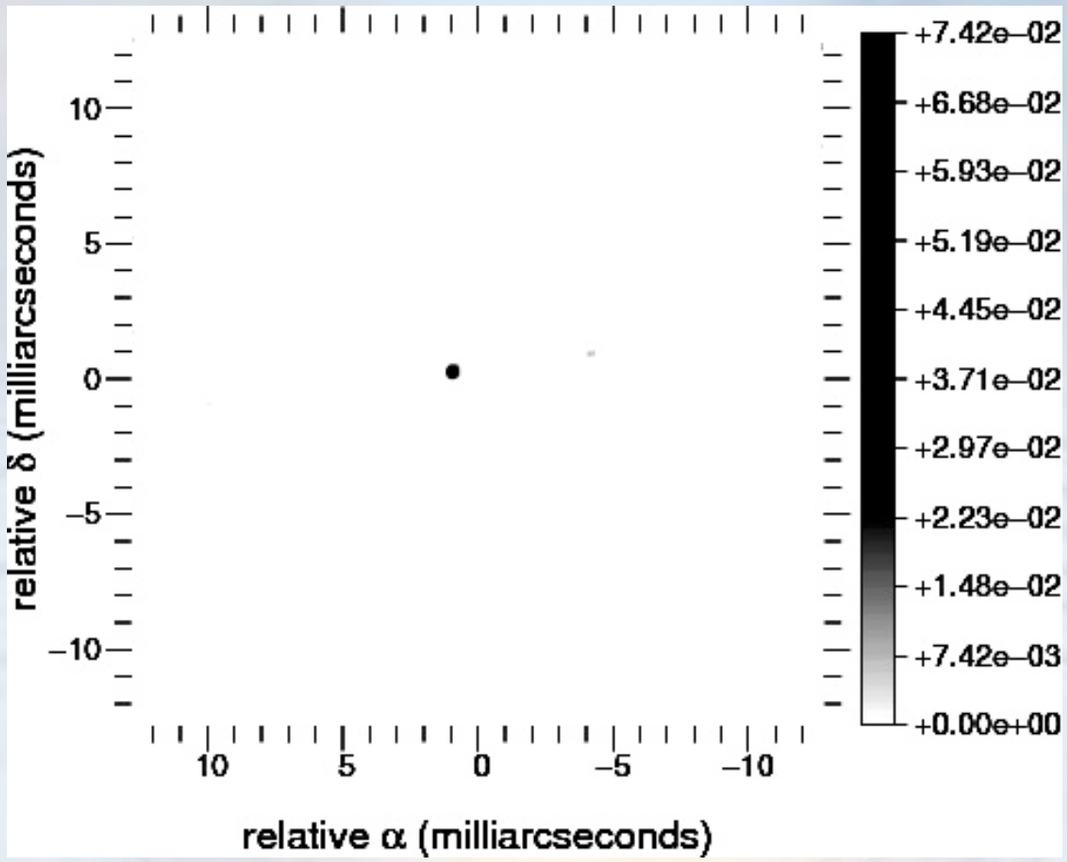


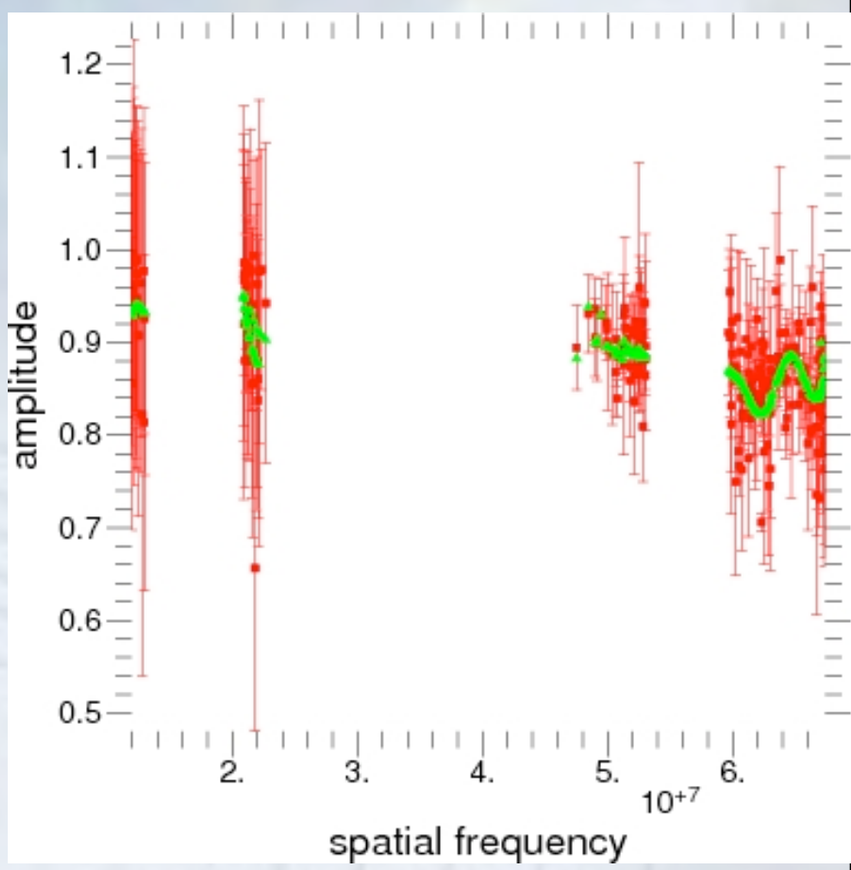
Malbet et al. (2005, A&A, 437, 627)

Image reconstruction of FU Ori data

Renard, Malbet & Thiébaut (in progress)







- Image reconstruction performed without any *a priori*
- The image reconstruction process finds the wiggle in the data
- First run, work is still in progress

Origin of the unresolved source: low-mass companion (at the origin of the outburst, forming planet, wave in the disk,...)?

Image reconstruction of FU Ori data

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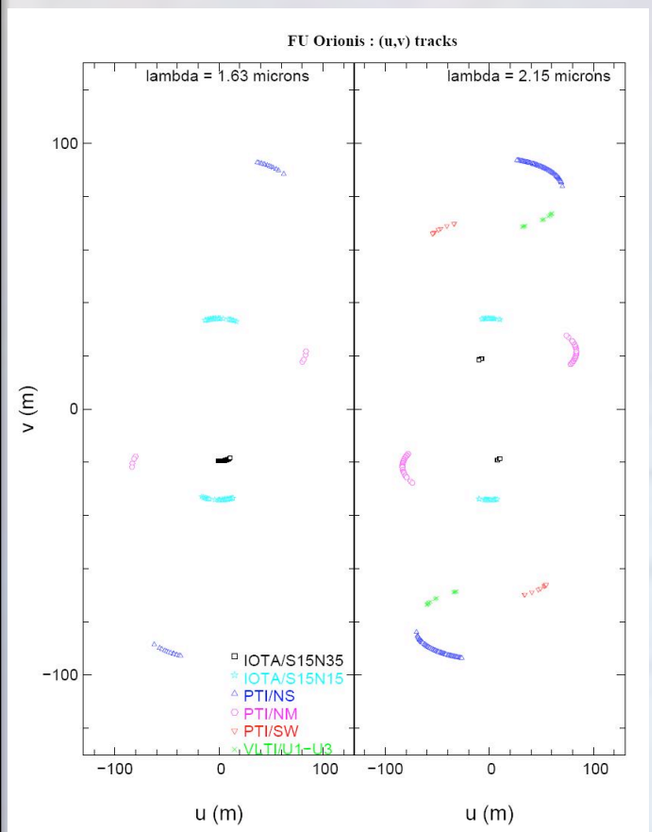

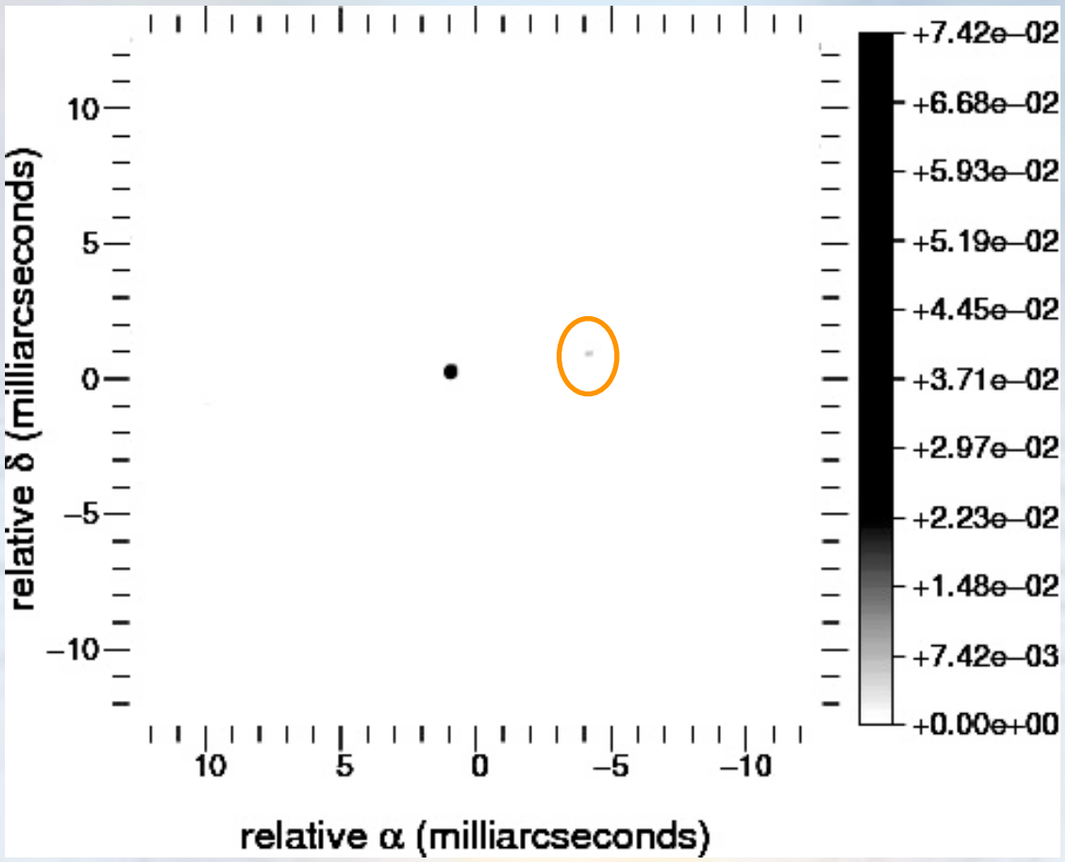

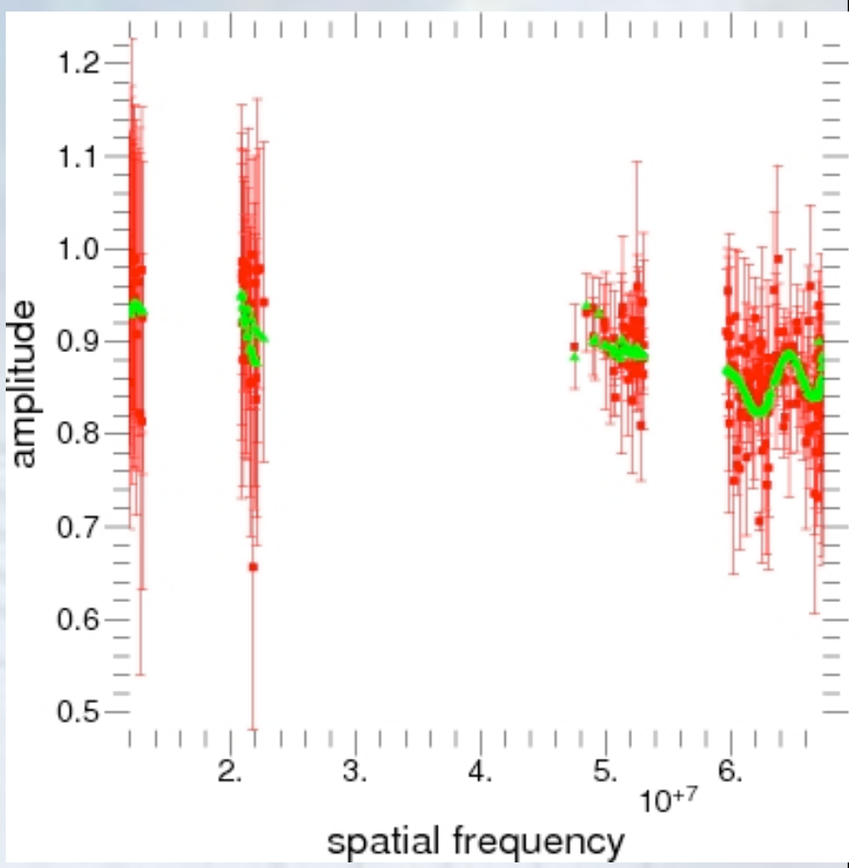

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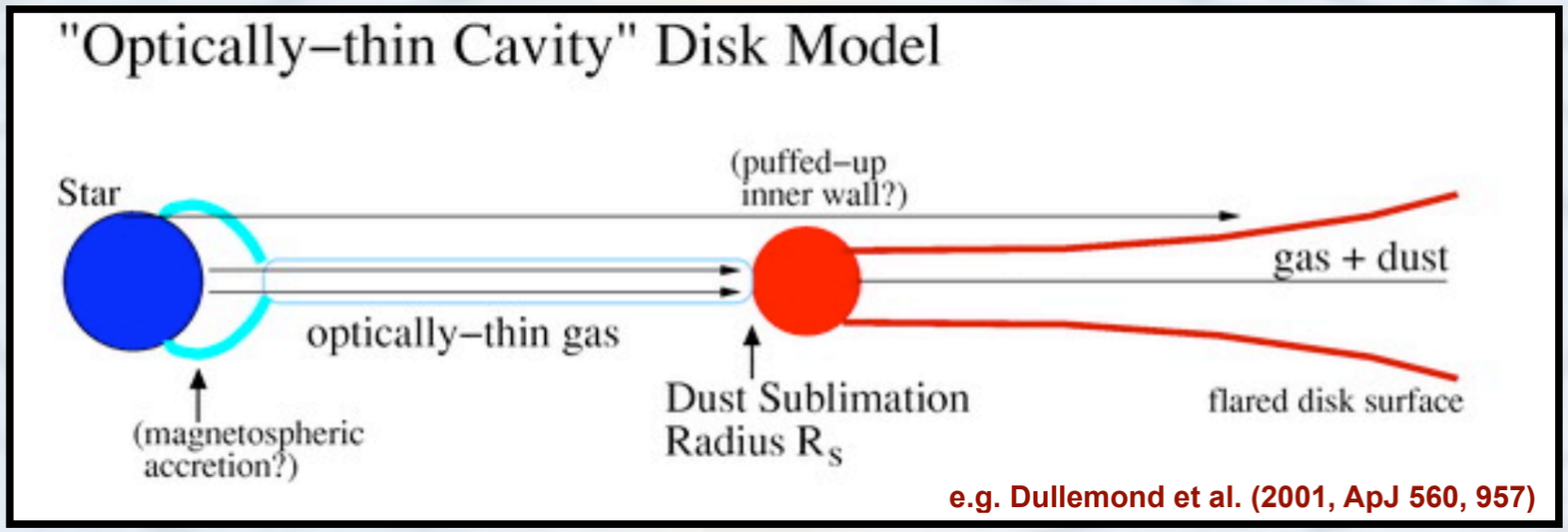
Origin of the unresolved source: low-mass companion (at the origin of the outburst, forming planet, wave in the disk,...)?

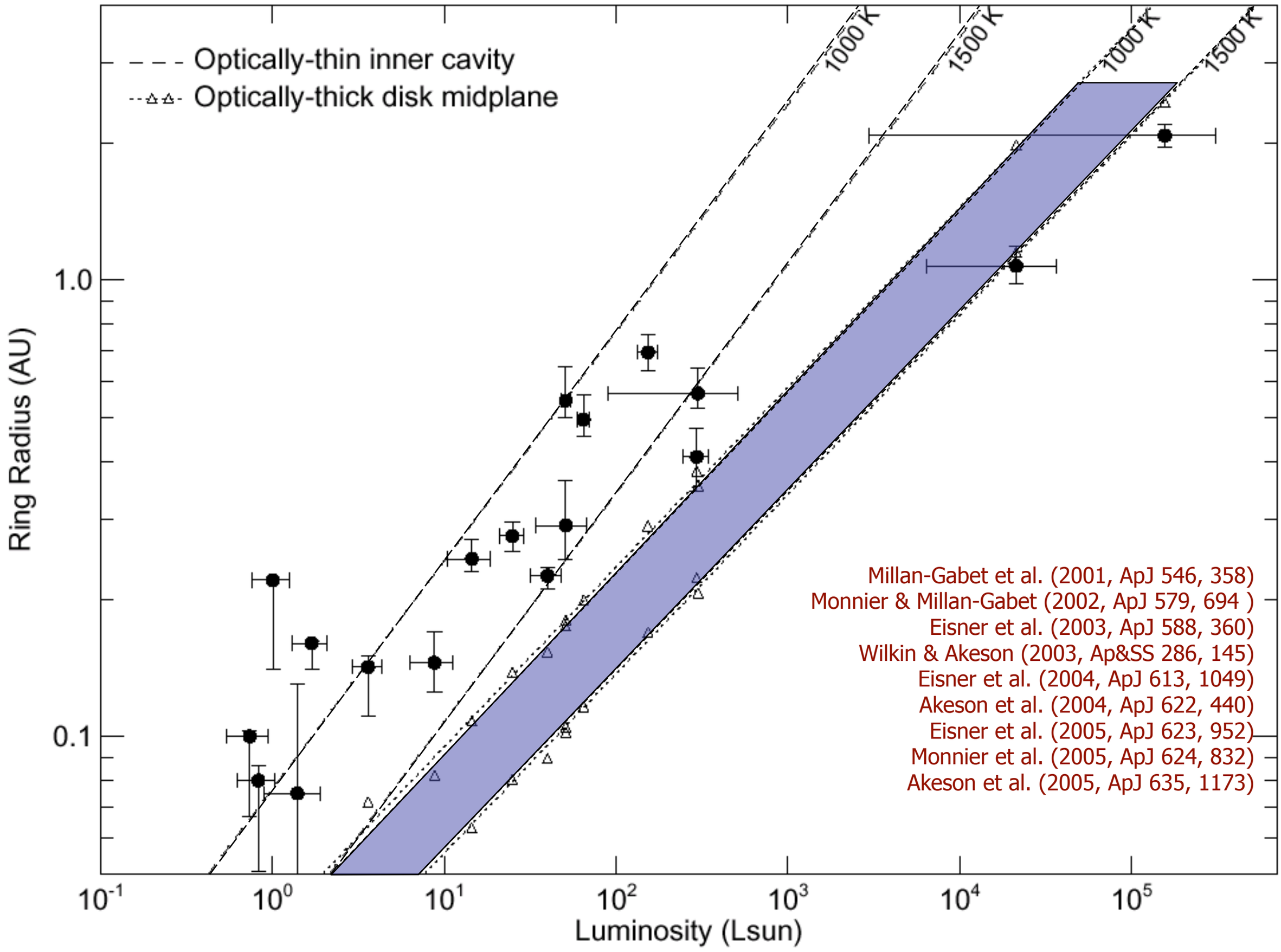
Inner regions of the disks

- In 2002, Monnier & Millan-Gabet measured the sizes of several HAeBe stars on IOTA.
- They found that the sizes correlate with the stellar luminosity as r^{-2}
- It could be explained as the consequences of dust sublimation at the inner edge of the disks



- This work was continued by several authors on different targets with PTI and KI.
- However several times, it did not match, in particular in the case of the less massive systems (T Tauri stars)

Near-IR Sizes of TTS and Herbig Ae/Be stars



Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
Eisner et al. (2003, ApJ 588, 360)
Wilkin & Akeson (2003, Ap&SS 286, 145)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
Eisner et al. (2005, ApJ 623, 952)
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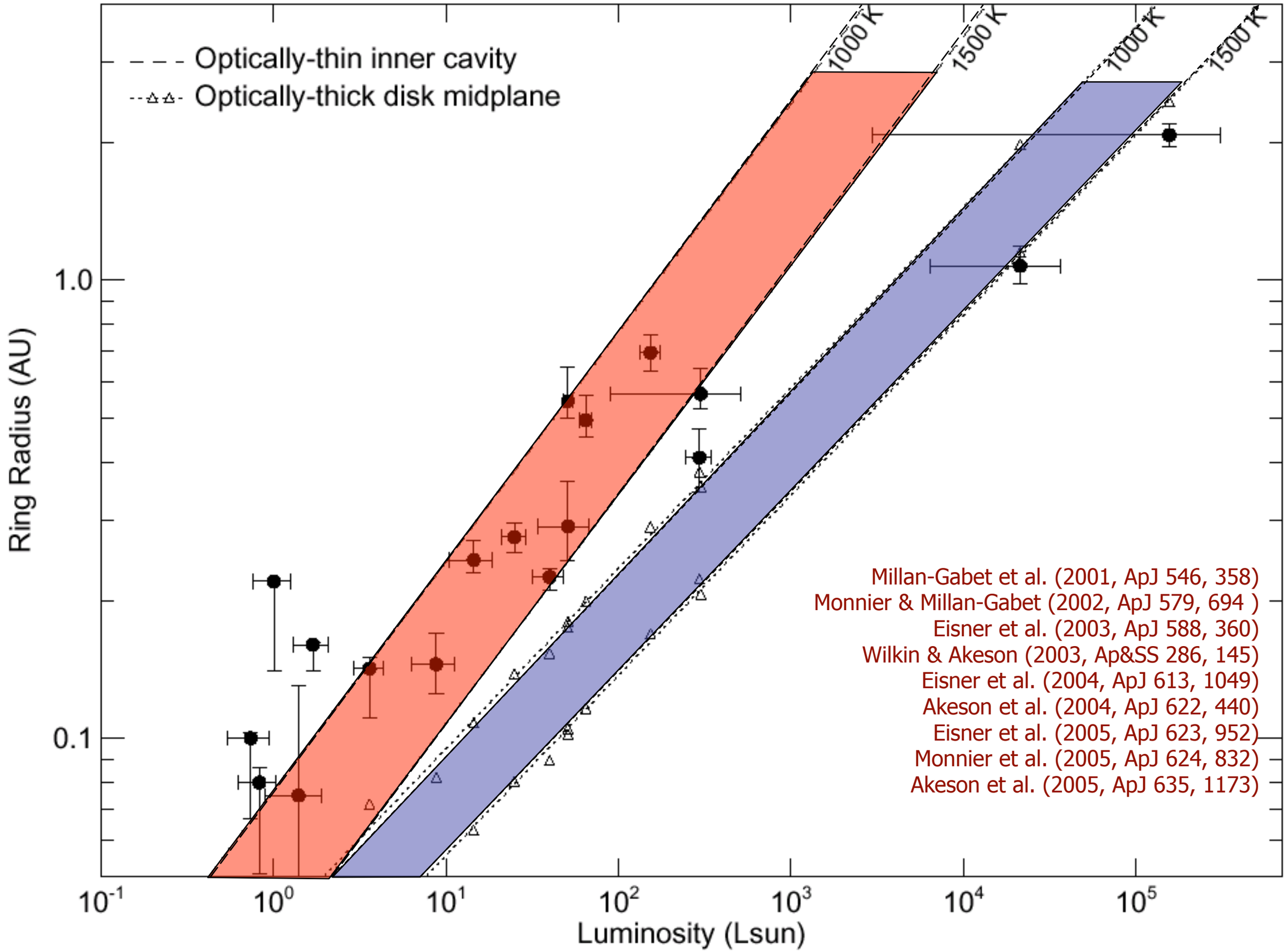

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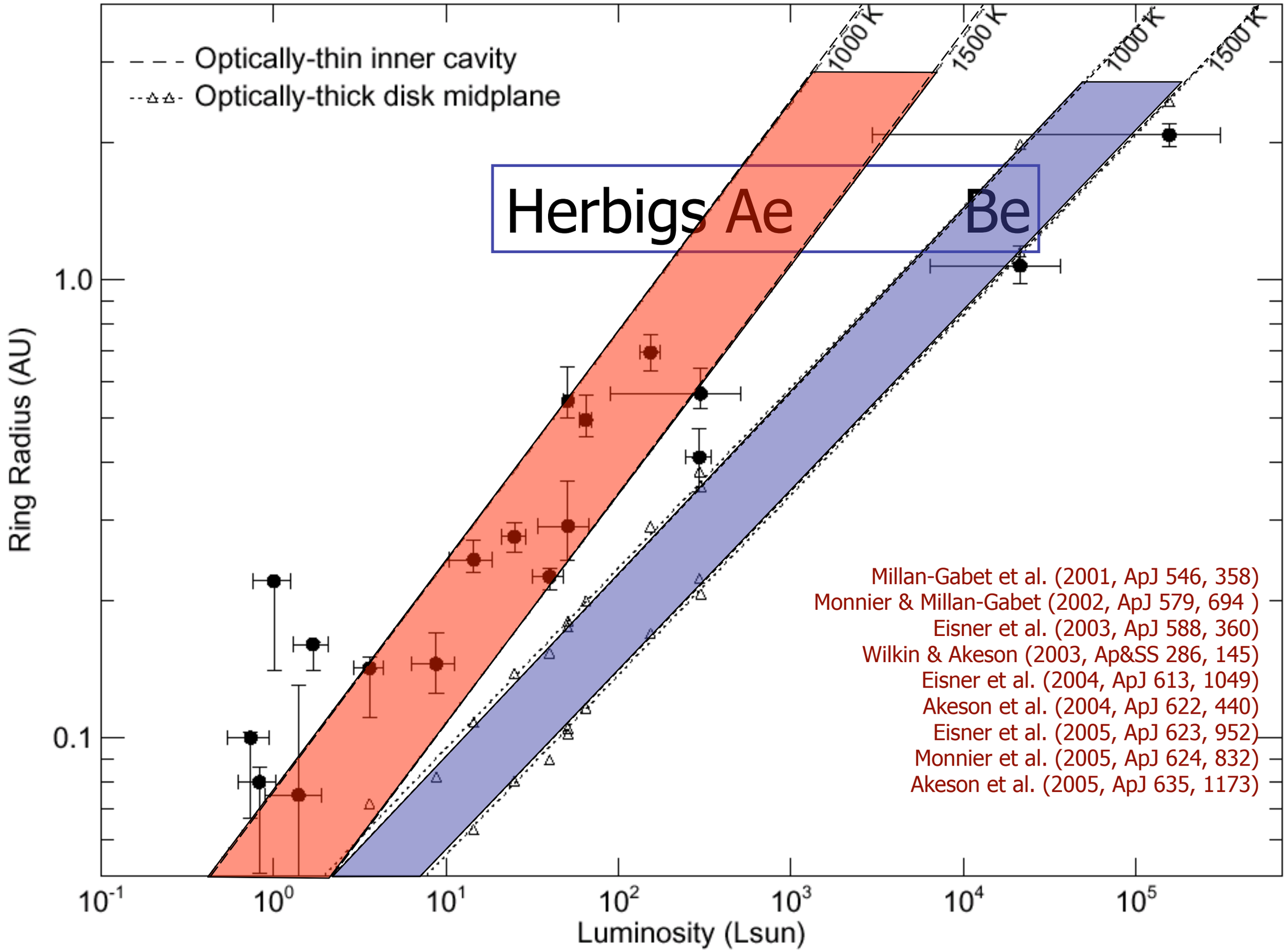

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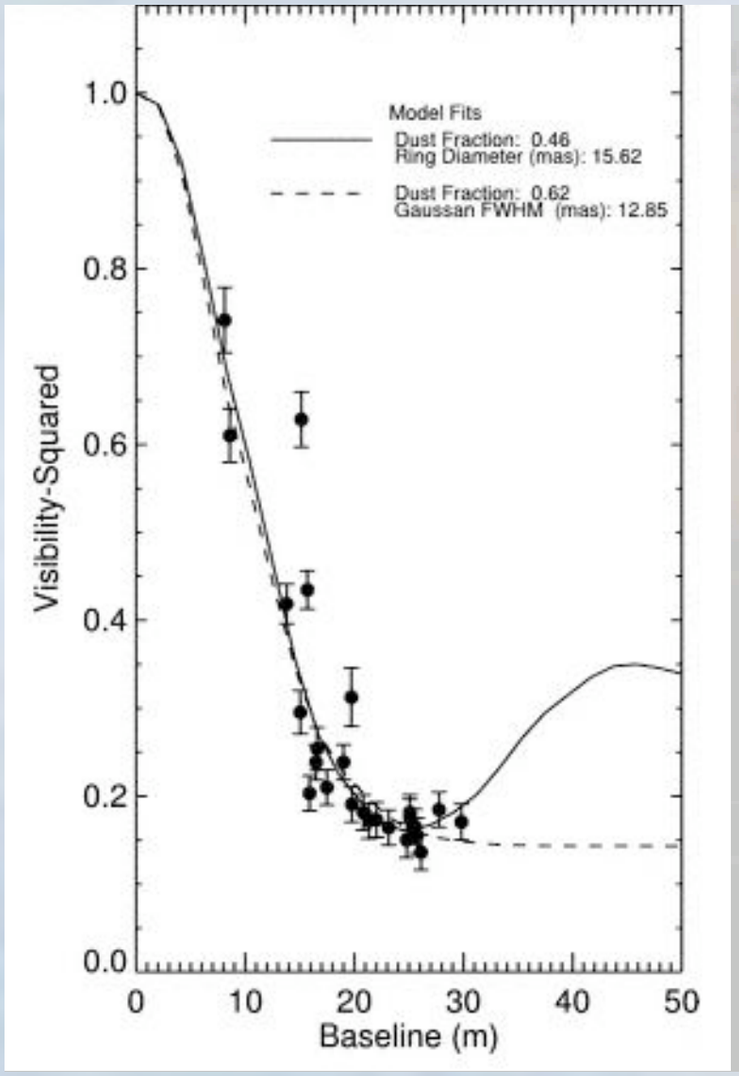
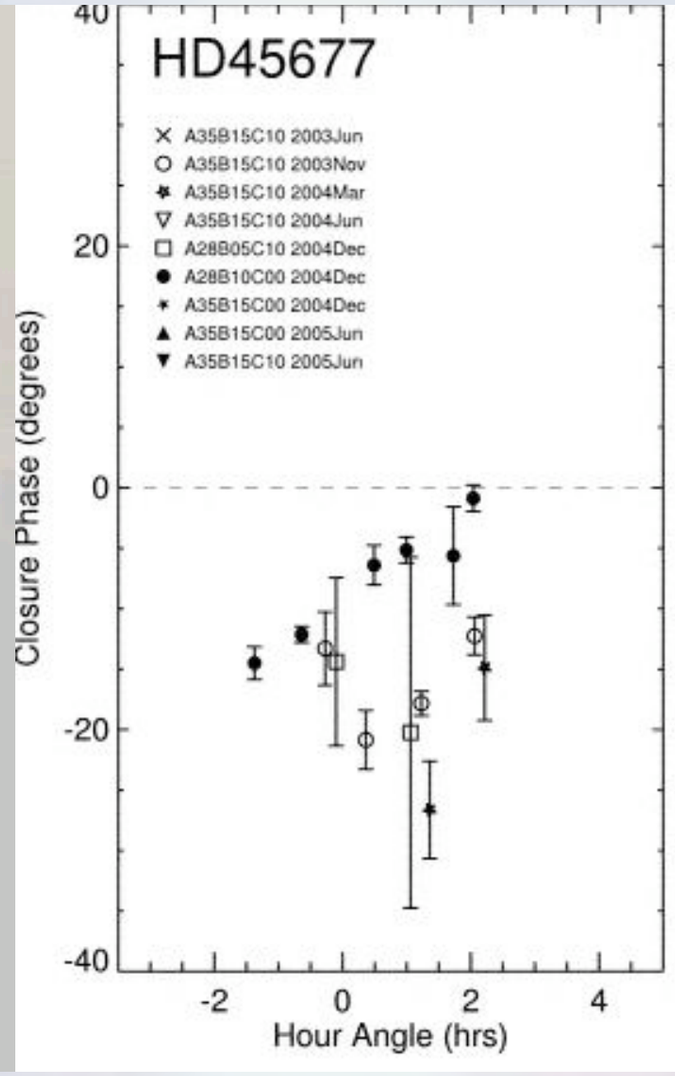
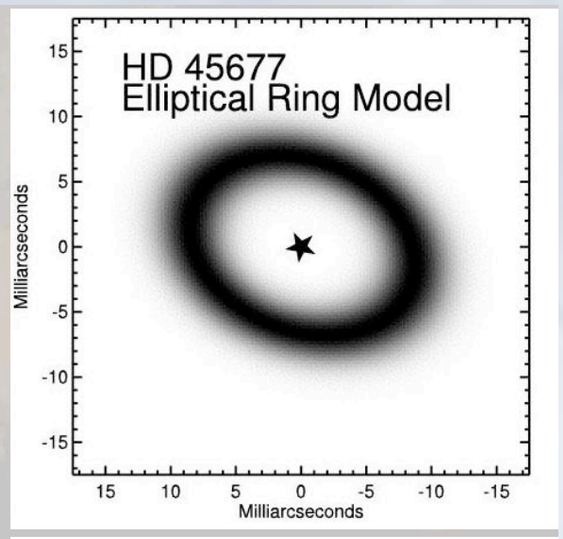
Geometry of the inner rim

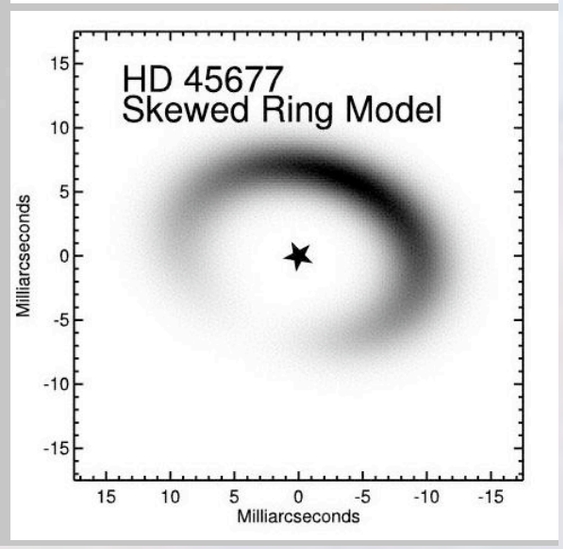
Geometry of the inner rim

- Closure phase observable can probe brightness asymmetries along the ring **Monnier et al. (2006, ApJ 646, 444)**

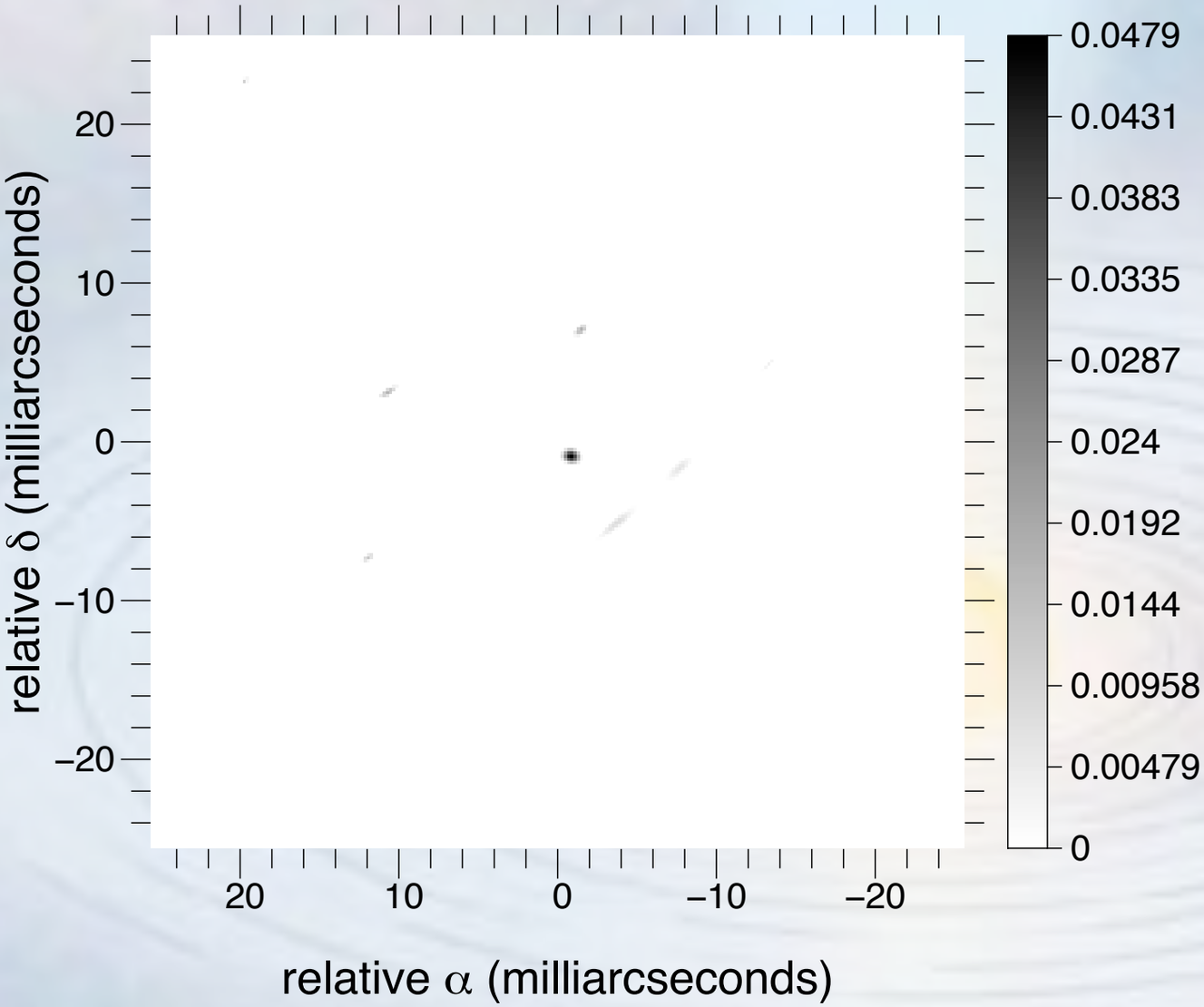




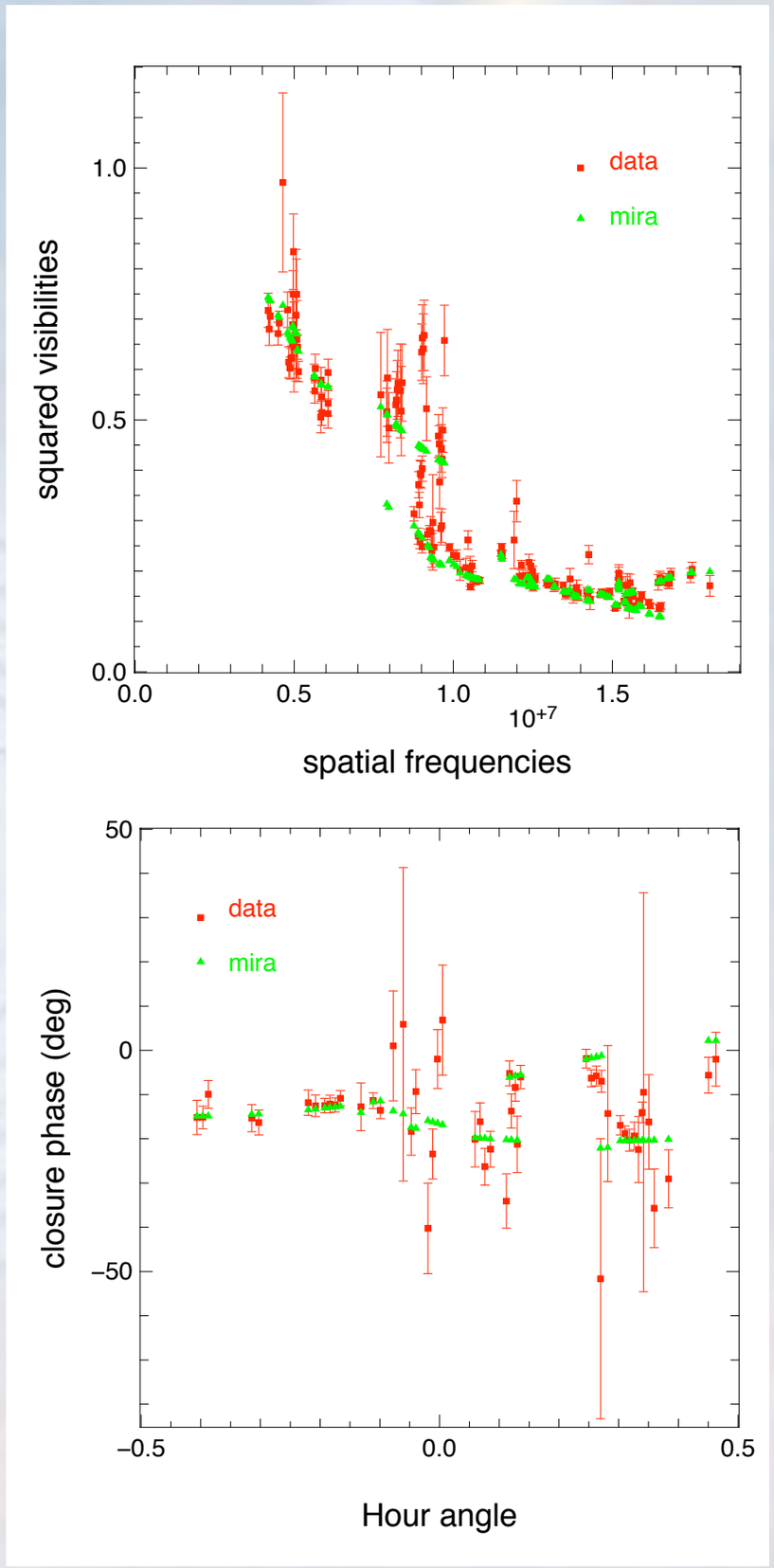




First image reconstruction for HD 45677

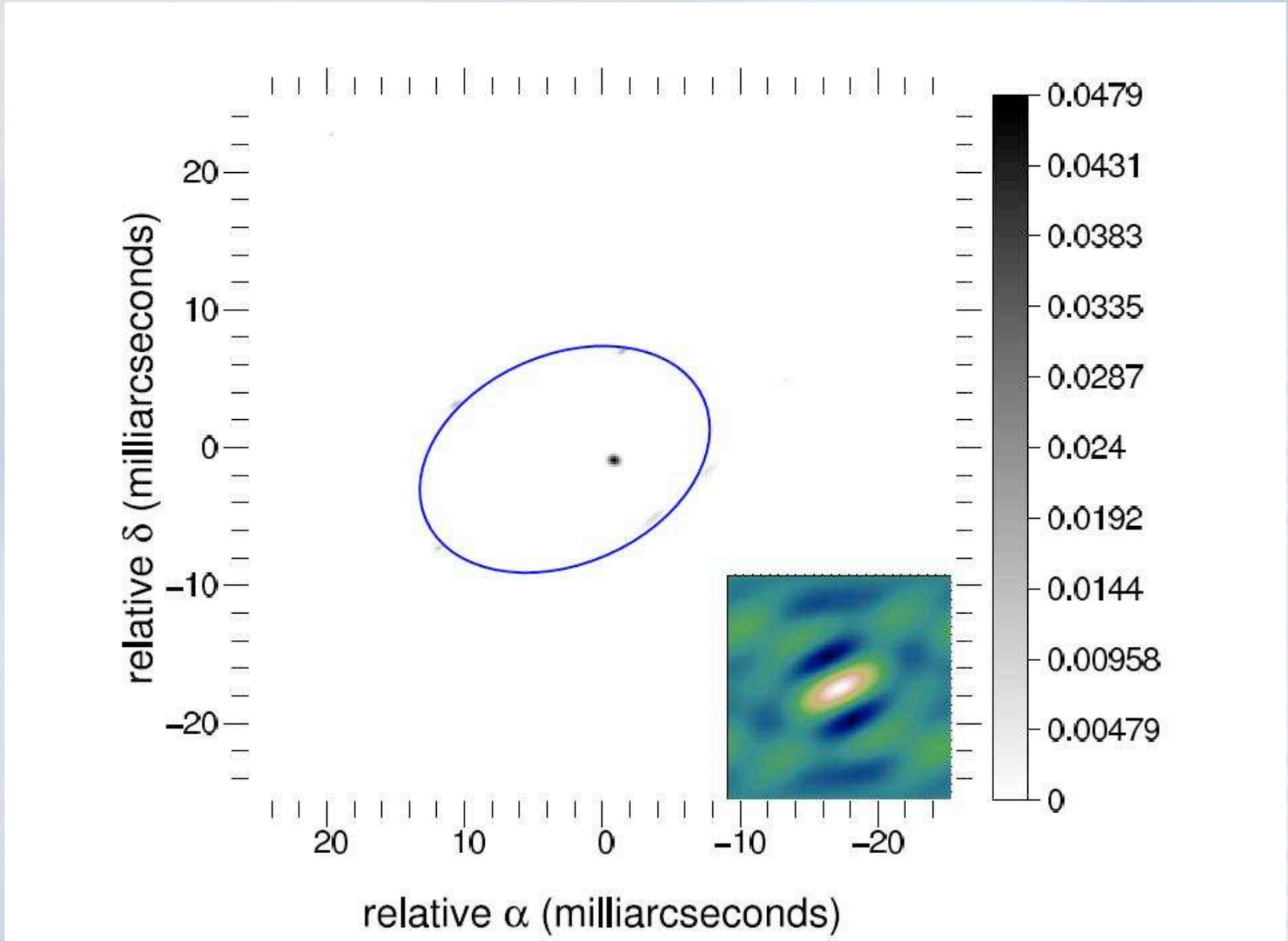


Renard, Malbet, Thiébaut & Berger (SPIE 2008)



Work in progress...

First image reconstruction for HD 45677



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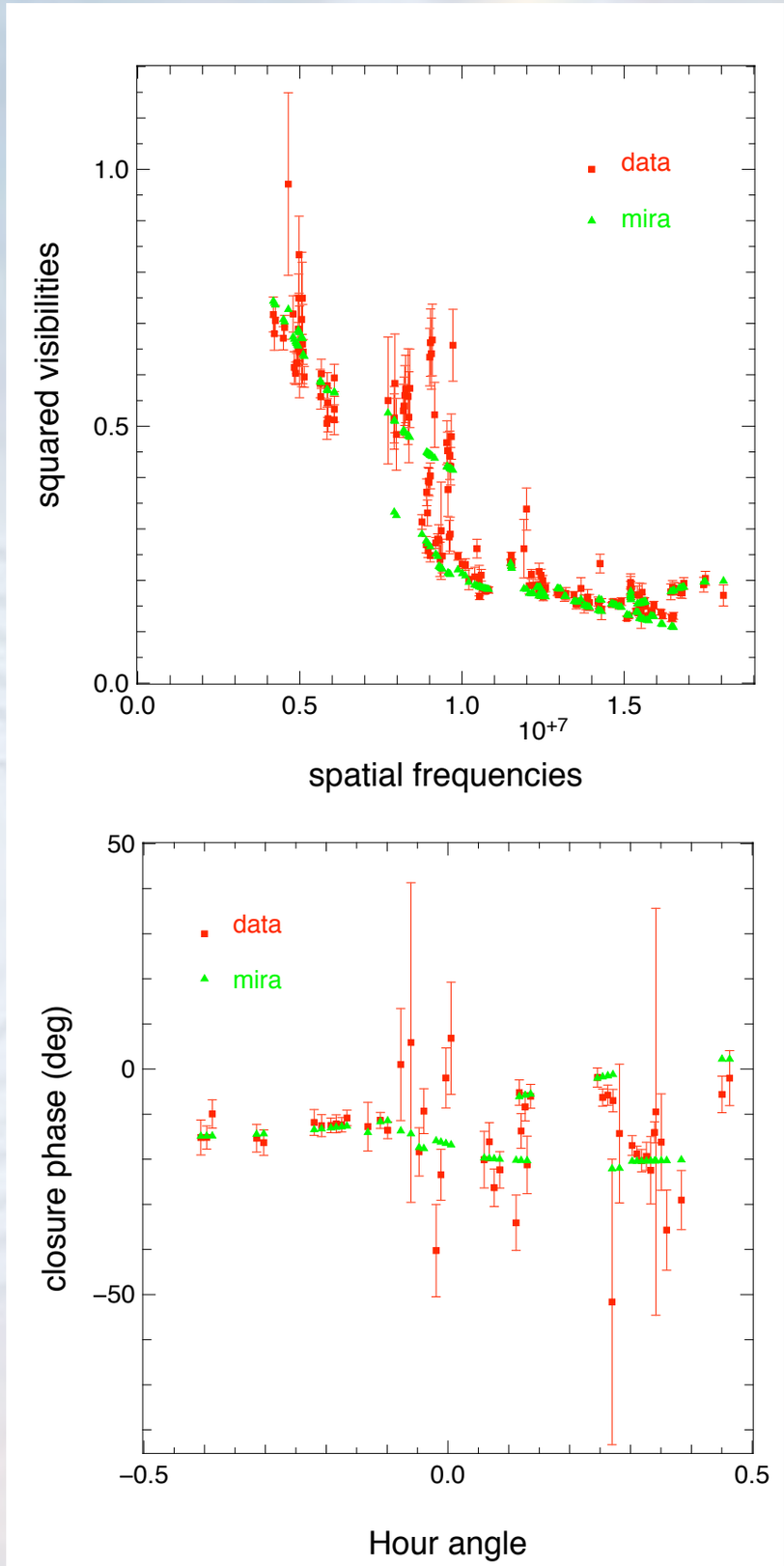
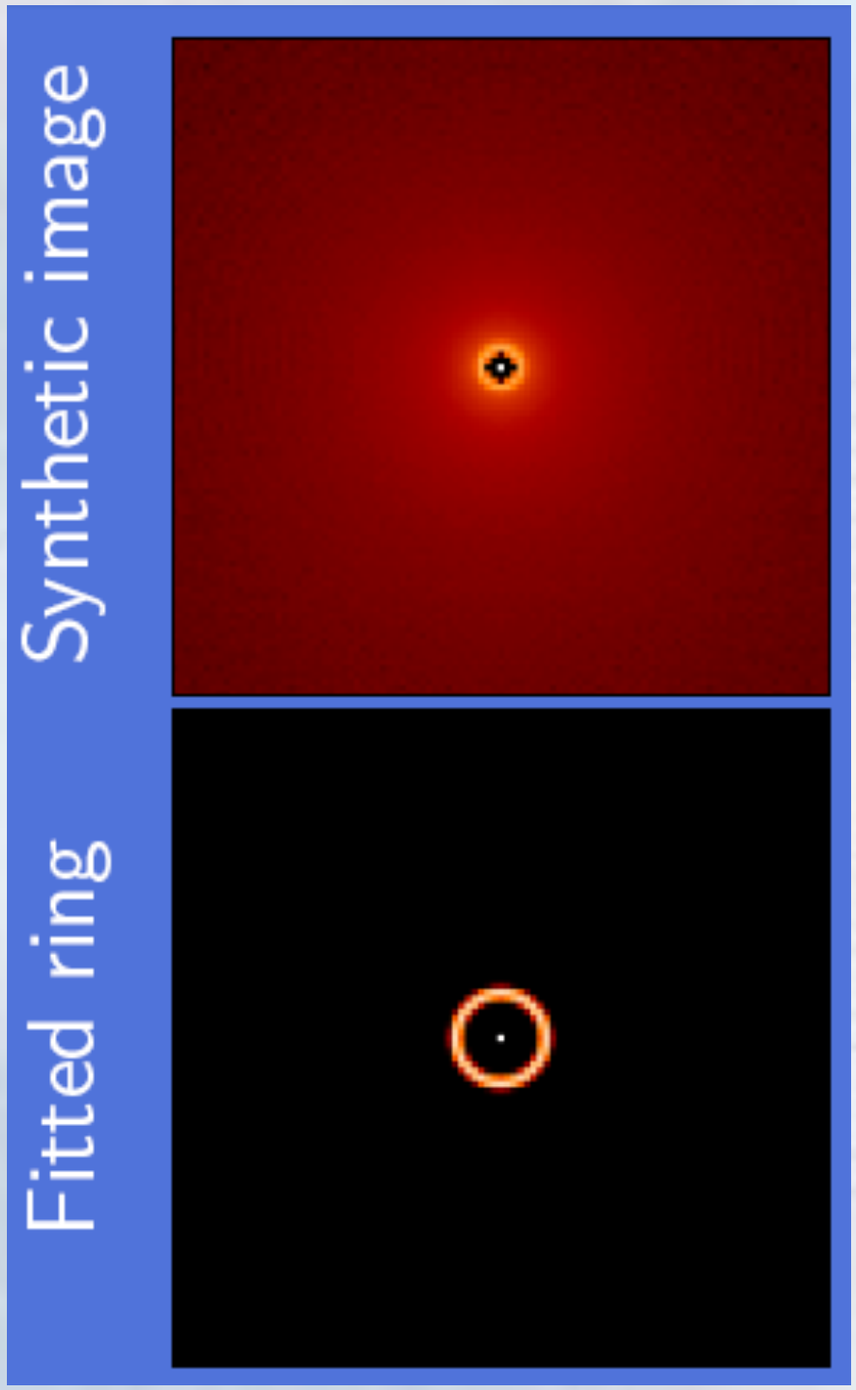
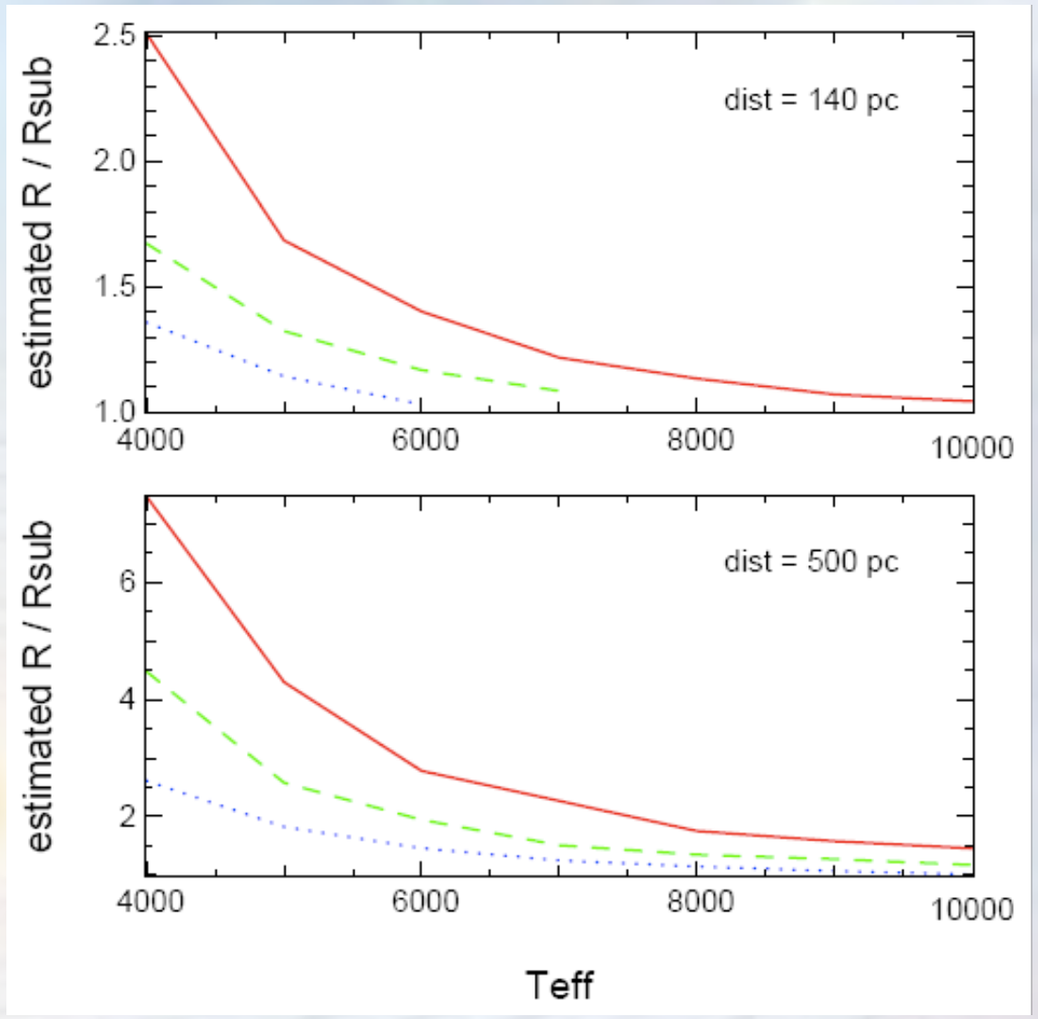


Work in progress...

Effect of extended scattered light



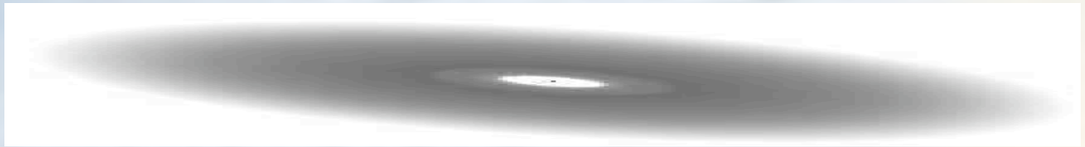


- Ring radius fitting can lead to overestimated sizes
- Careful modeling must be performed including all sources of radiation

Pinte et al. (2007, ApJ 673, L63)

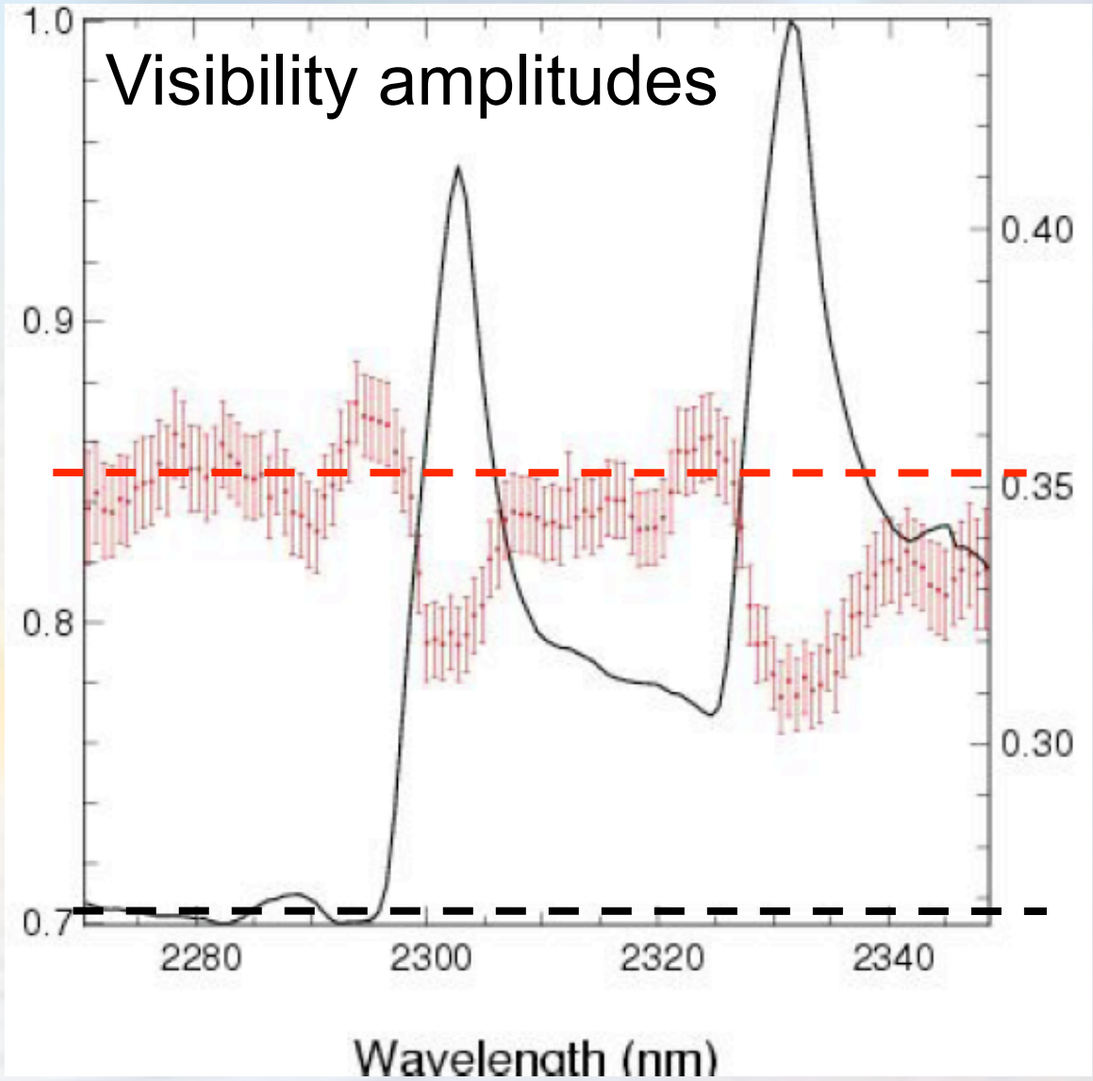
Detecting the hot molecular gas in 51 Oph

- IR excess: optically thin circumstellar dust disk?
- CO overtone lines @ 2.3μm: gas in keplerian rotation in the first UA [Thi et al. 2005]
- High rotational velocity (*v*.sin *i* = 270km/s)



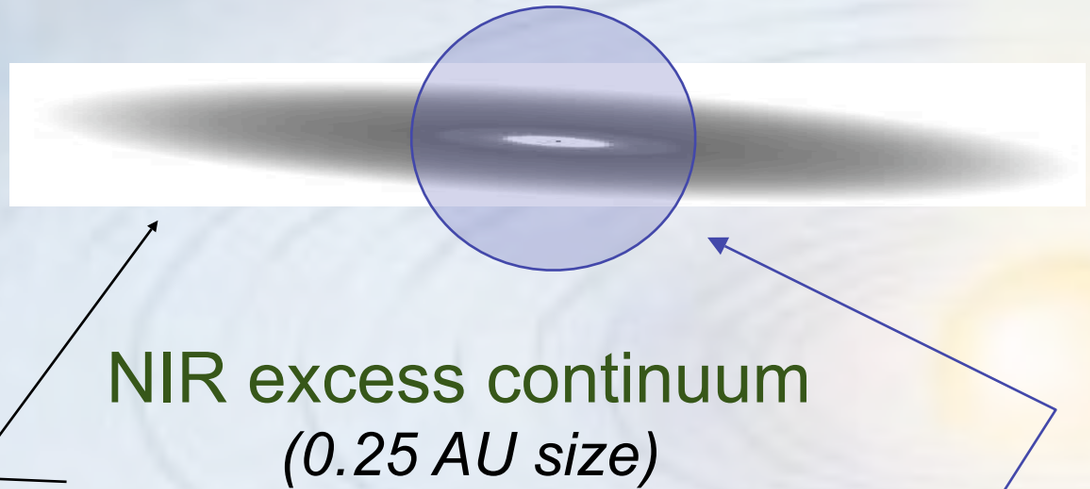
NIR excess continuum
(0.25 AU size)

Tatulli, et al. (2007, A&A in press)

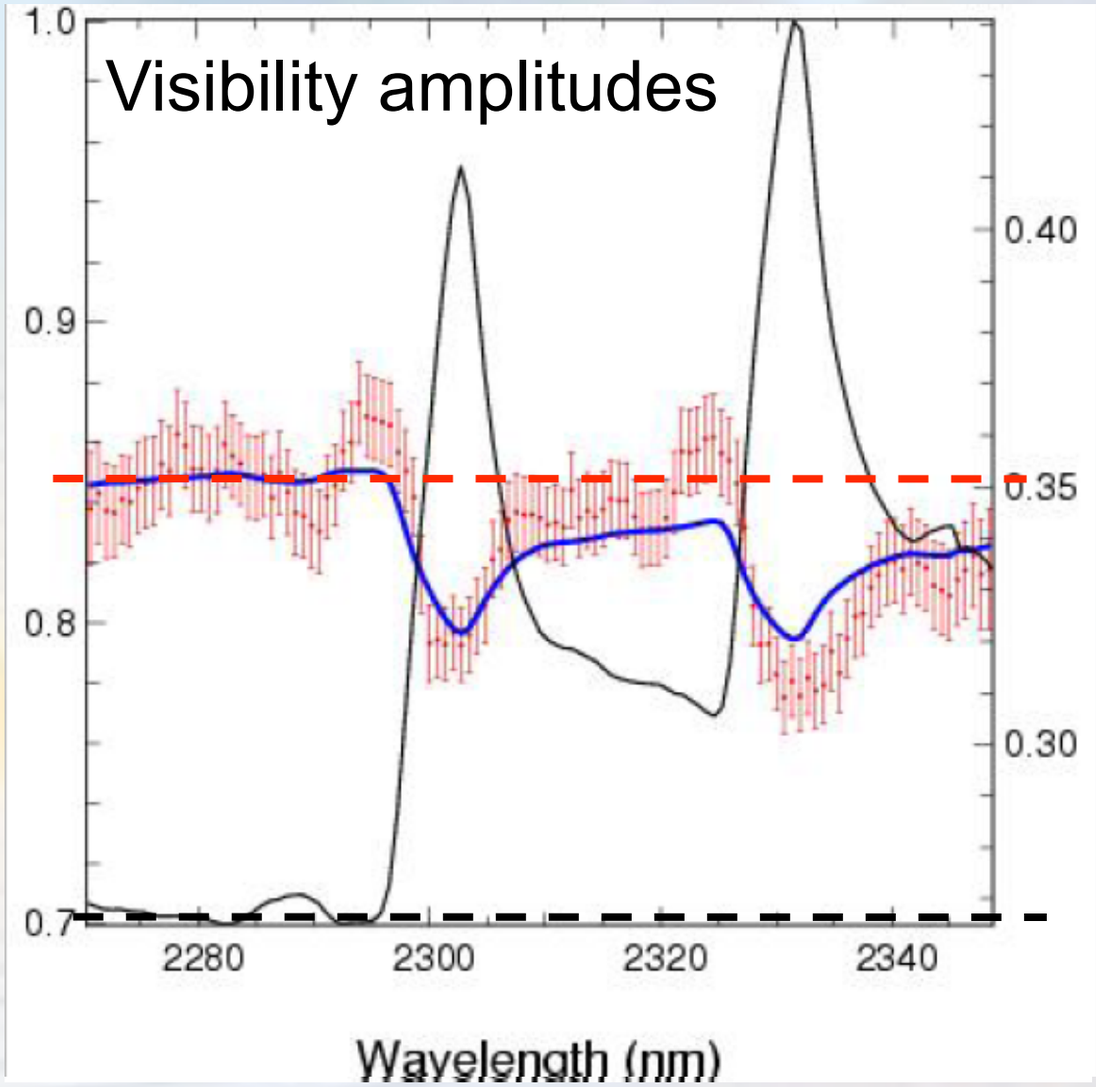


Detecting the hot molecular gas in 51 Oph

- IR excess: optically thin circumstellar dust disk?
- CO overtone lines @ 2.3μm: gas in keplerian rotation in the first UA [Thi et al. 2005]
- High rotational velocity (*v*.sin *i* = 270km/s)



Tatulli, et al. (2007, A&A in press)



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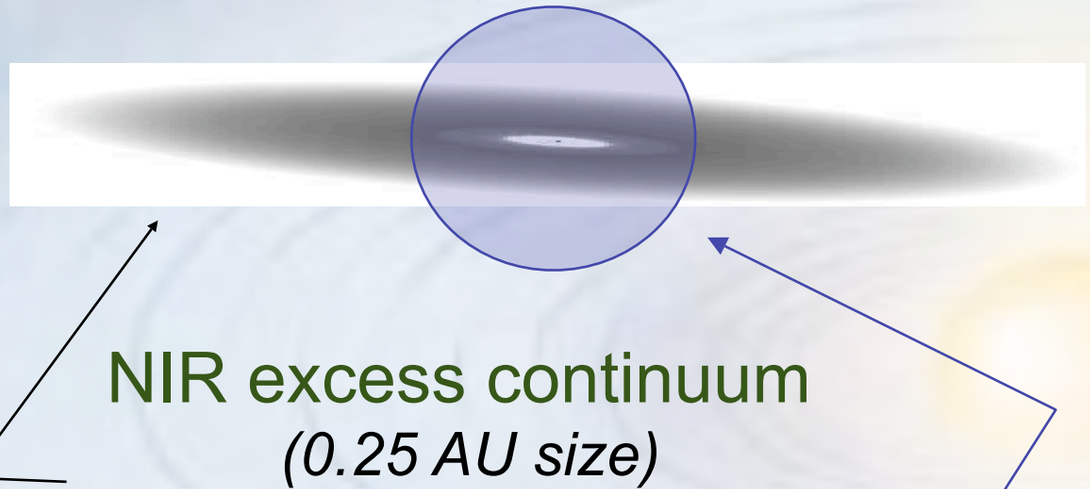

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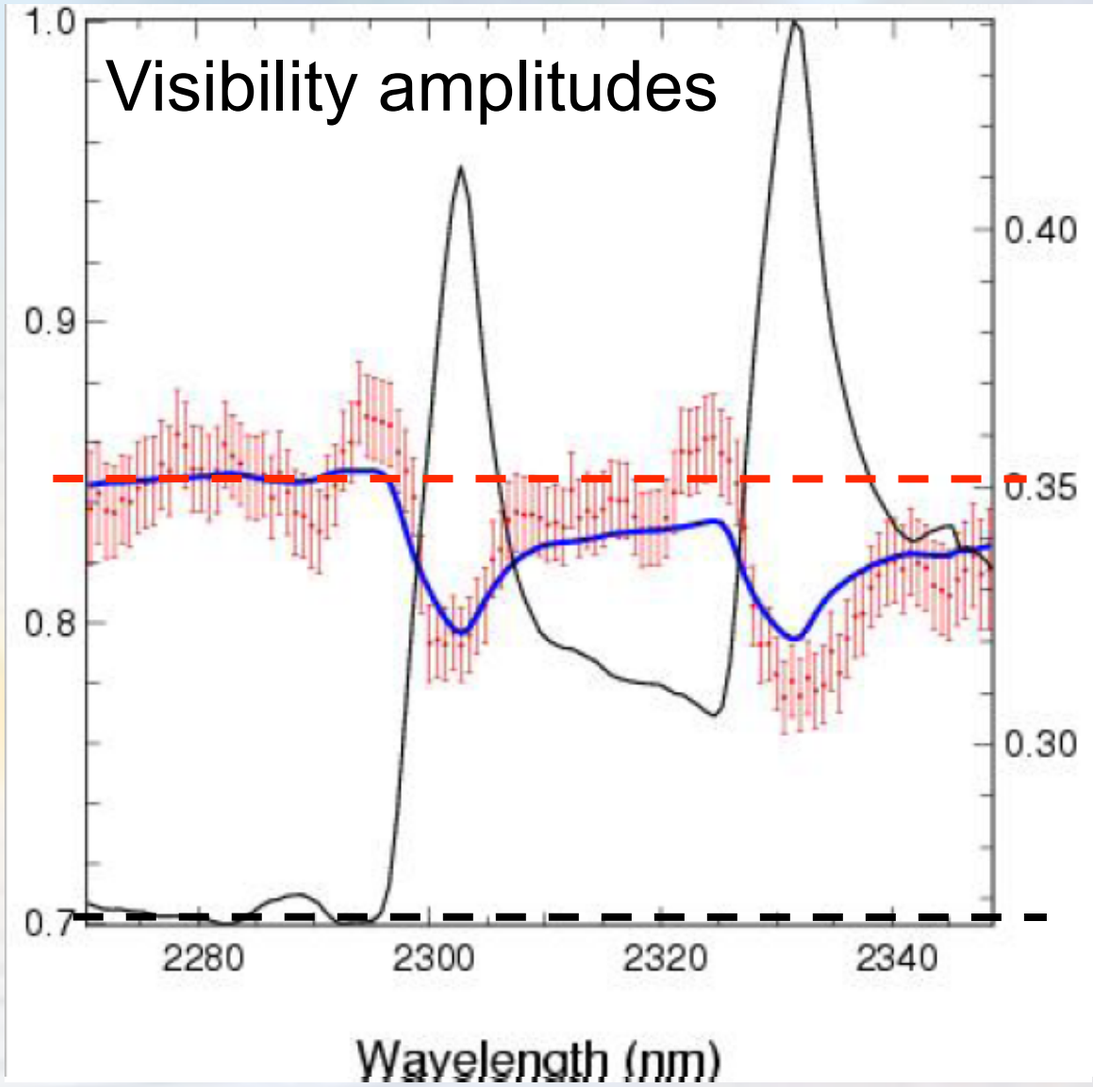
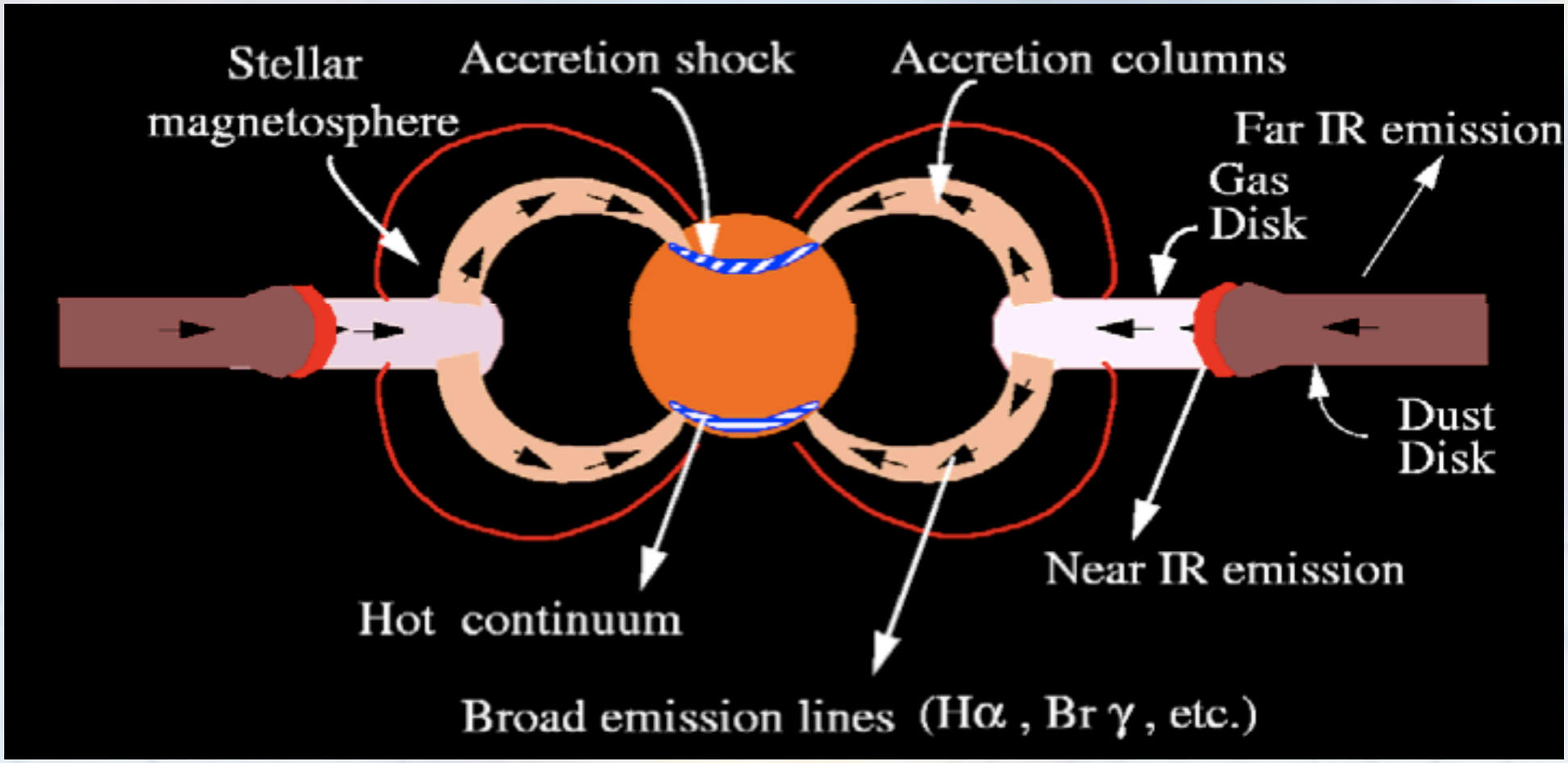


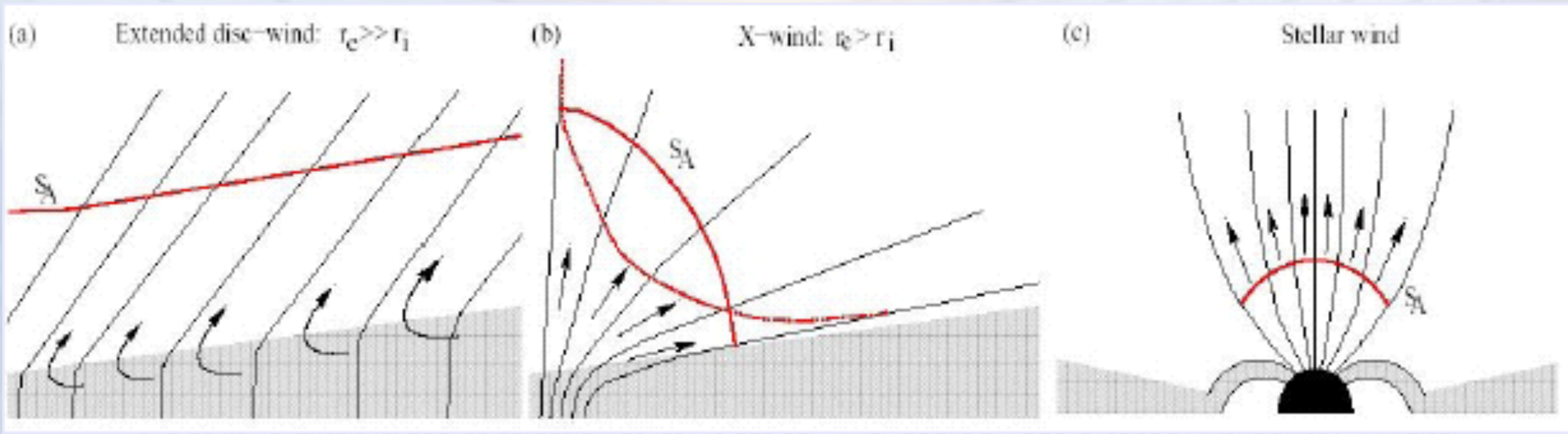
This is not the first time that there is clue for gas in the inner hole of the disk (cf. Akeson, Tannirkulam,...) but this is the first time dust and gas are spectrally and spatially separated.

ORIGIN of HYDROGEN EMISSION LINES?

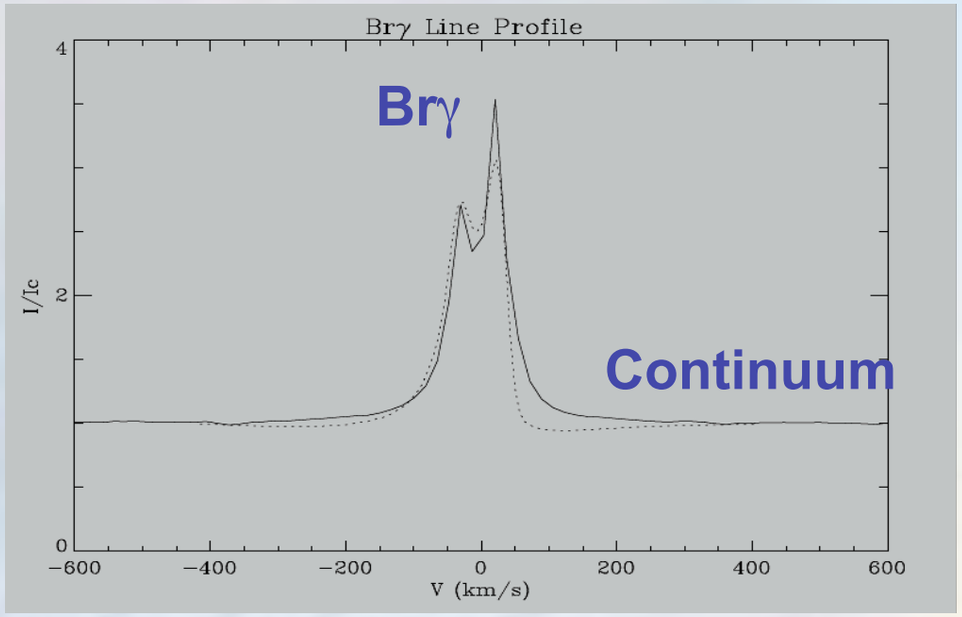
– Outflowing winds ?
– Magnetospheres ?

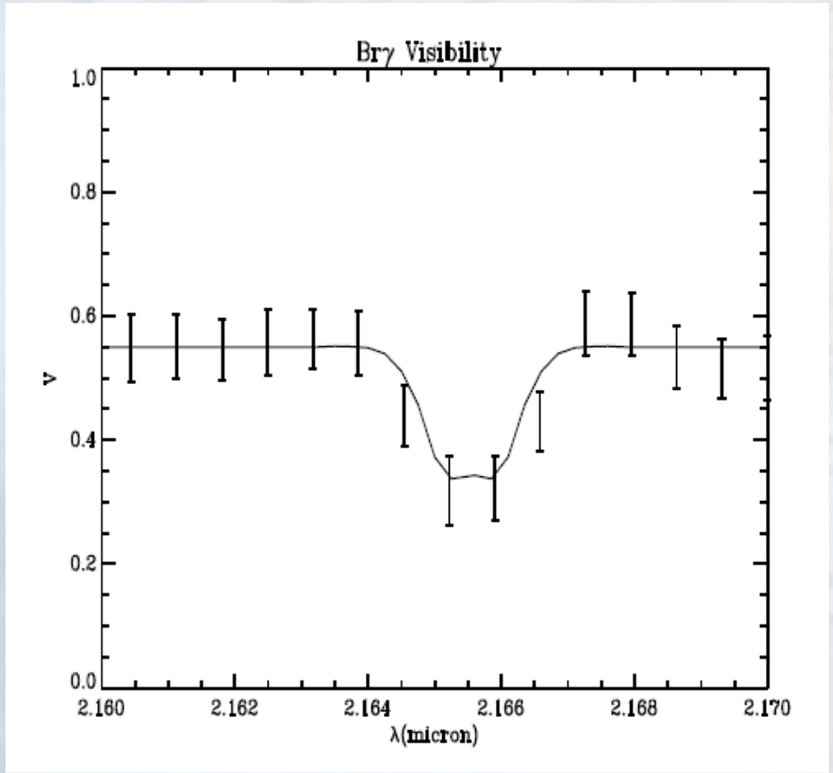
Disk/star interaction ?





Disk and wind spatially are spectrally resolved in MWC 297





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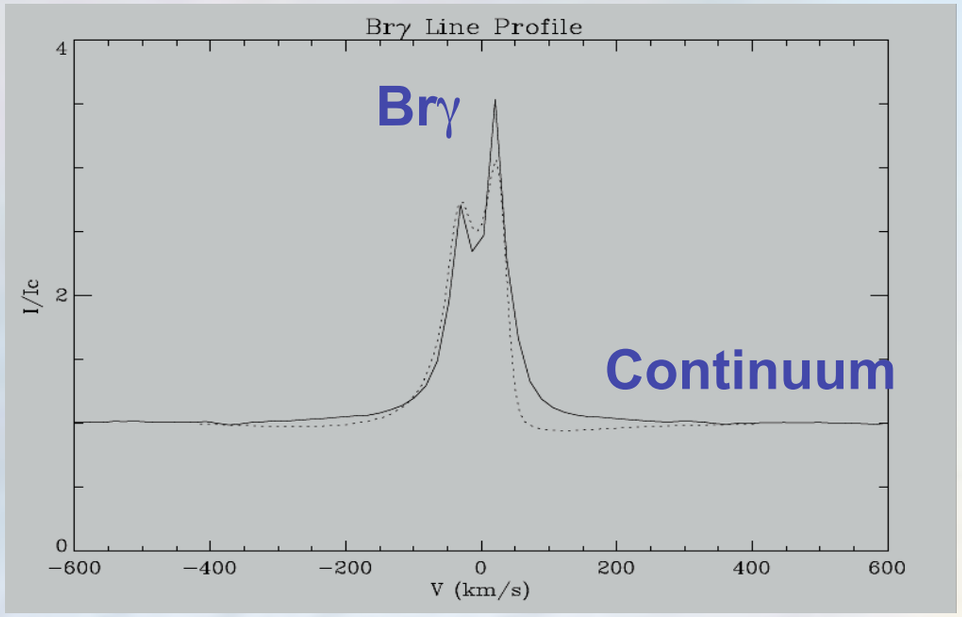
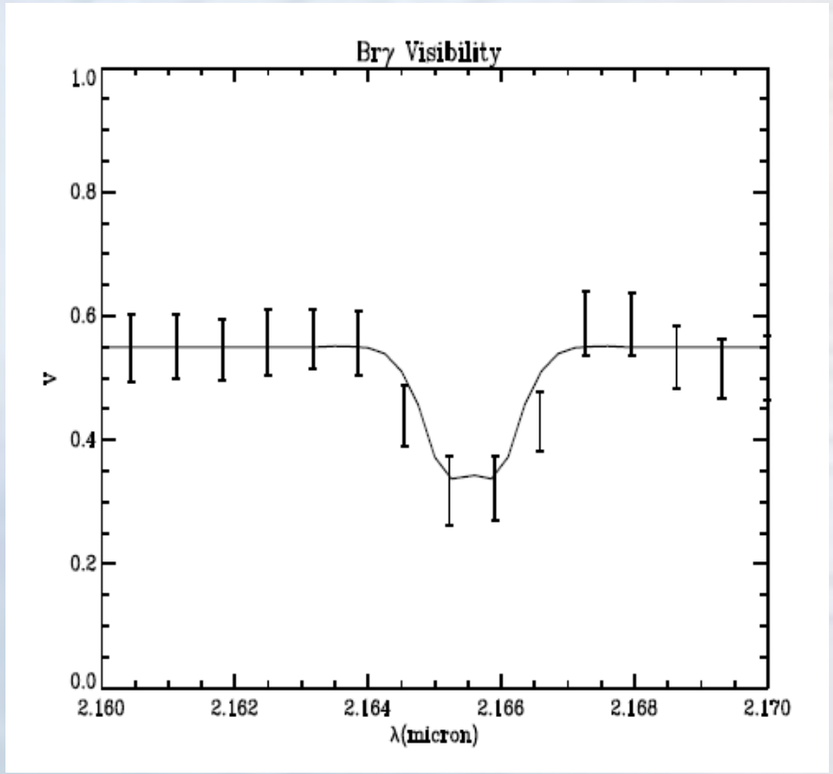
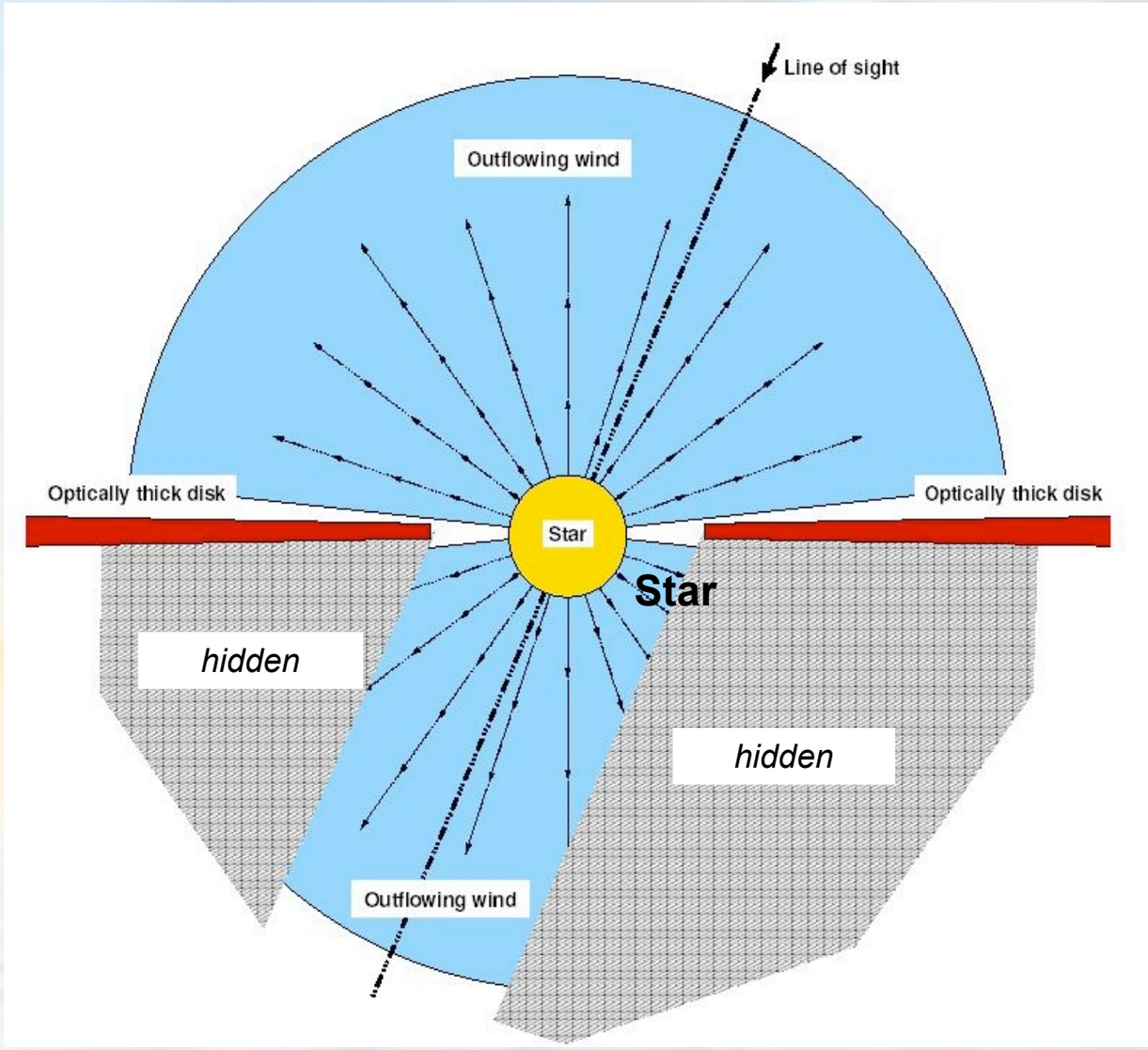
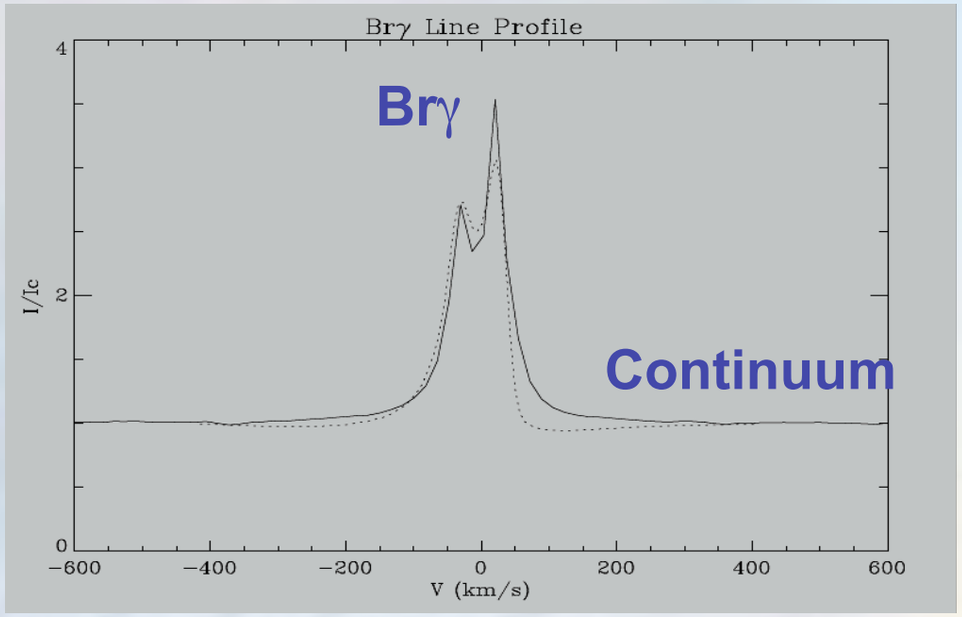


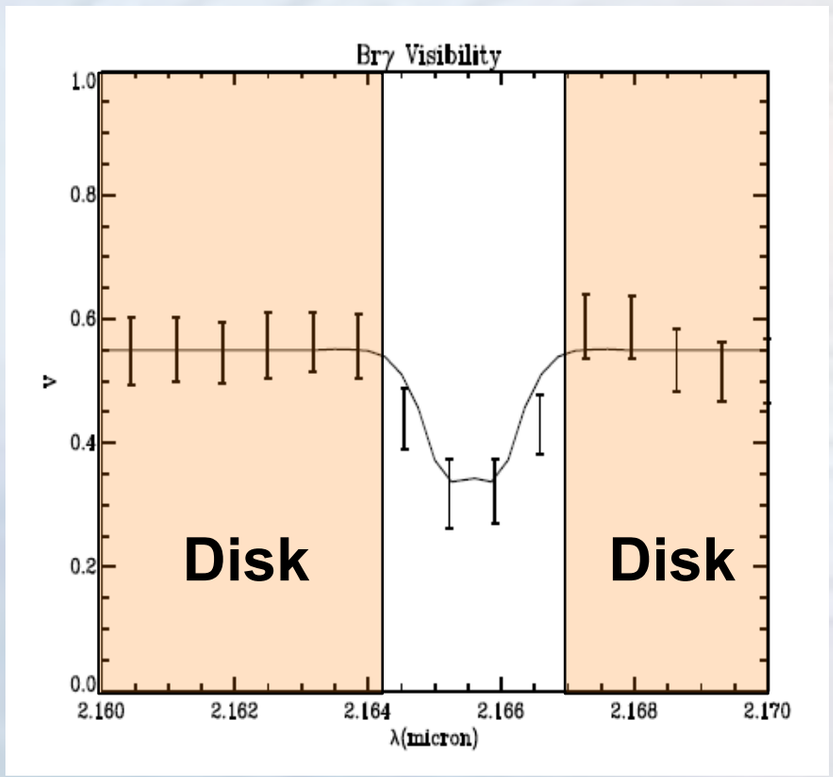


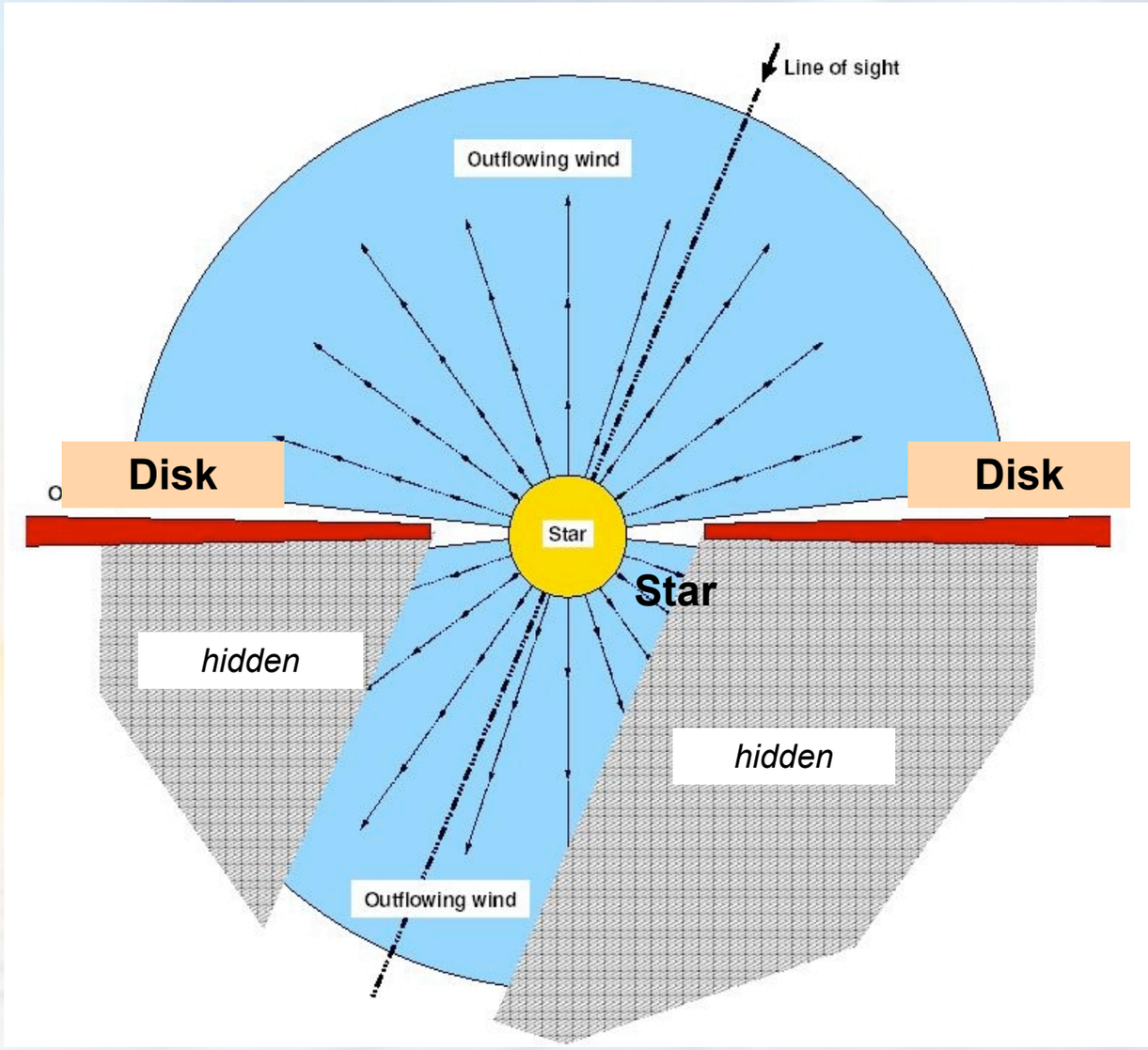


Malbet et al. (2007, A&A 464, 43)

Disk and wind spatially are spectrally resolved in MWC 297







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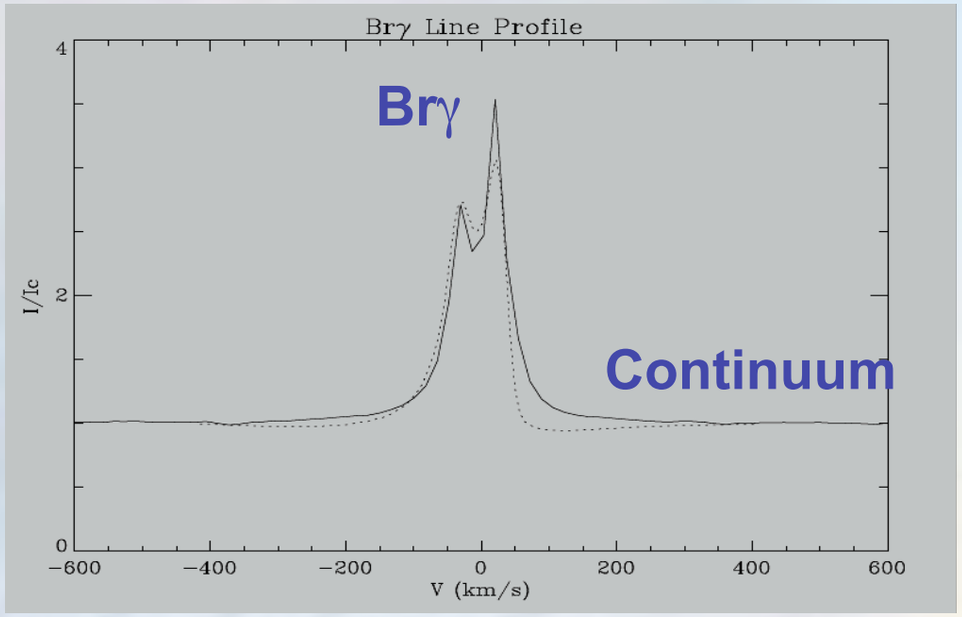

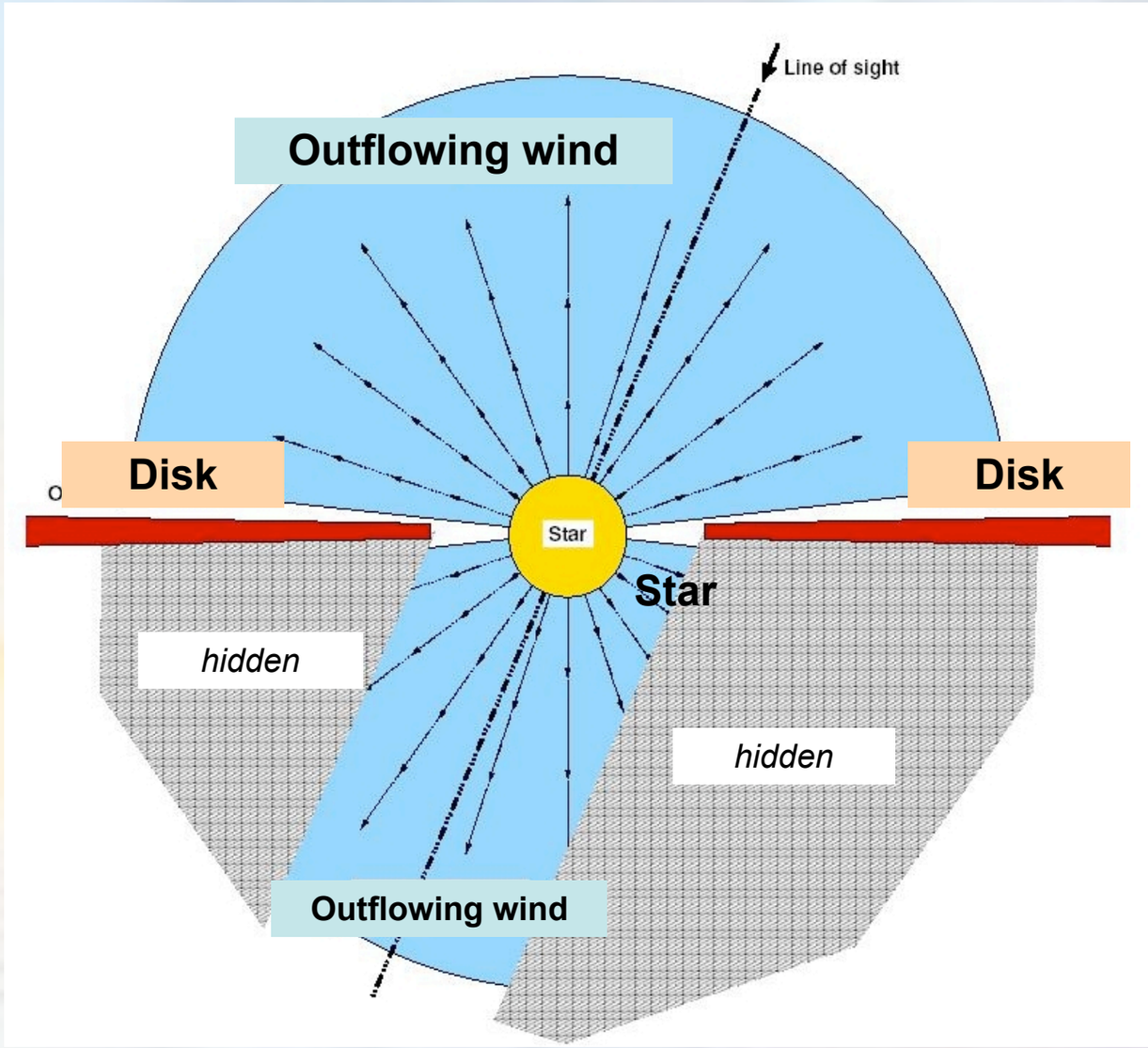

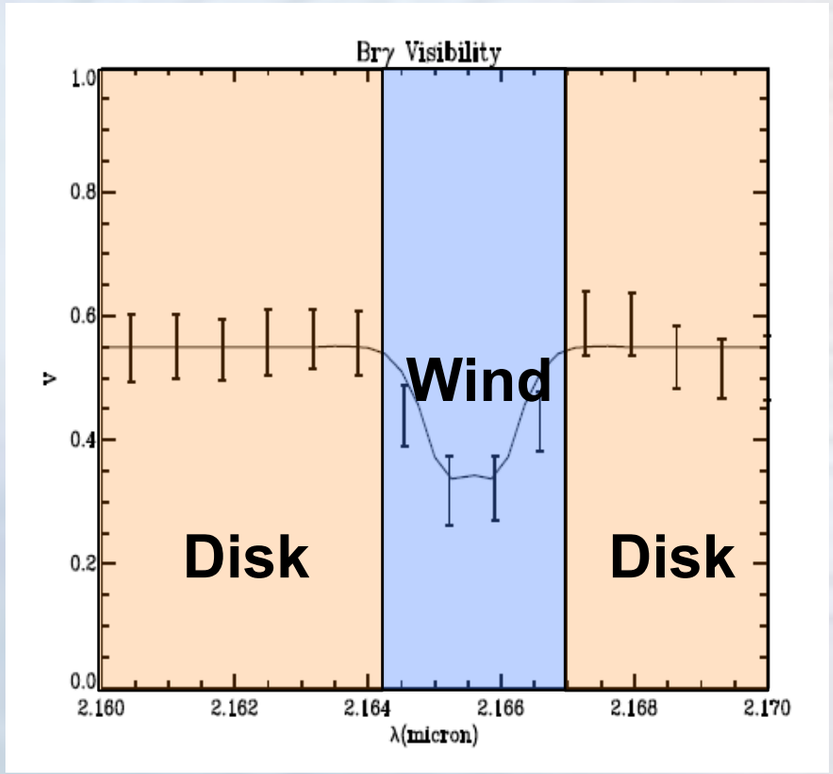

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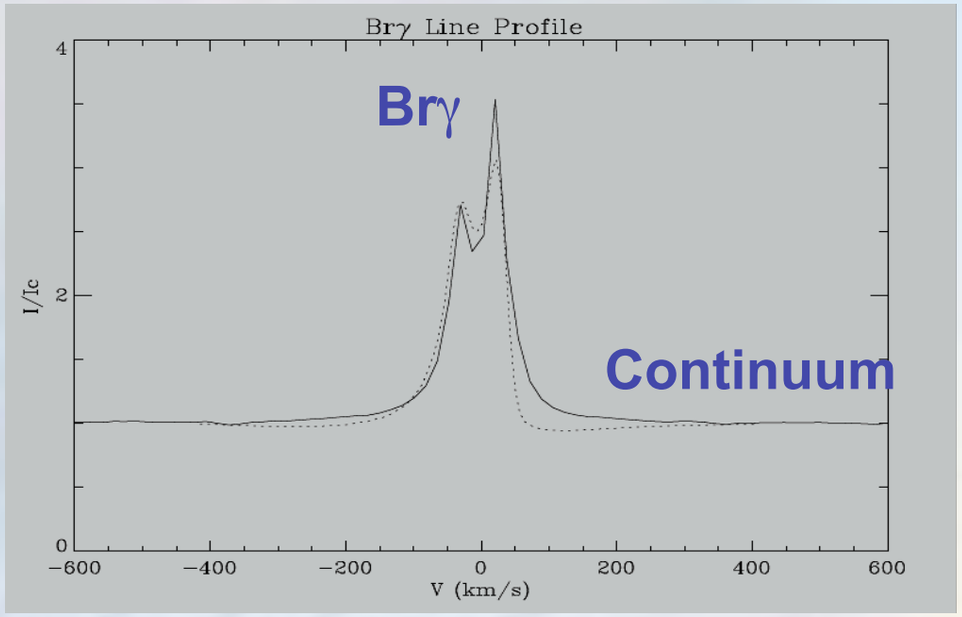
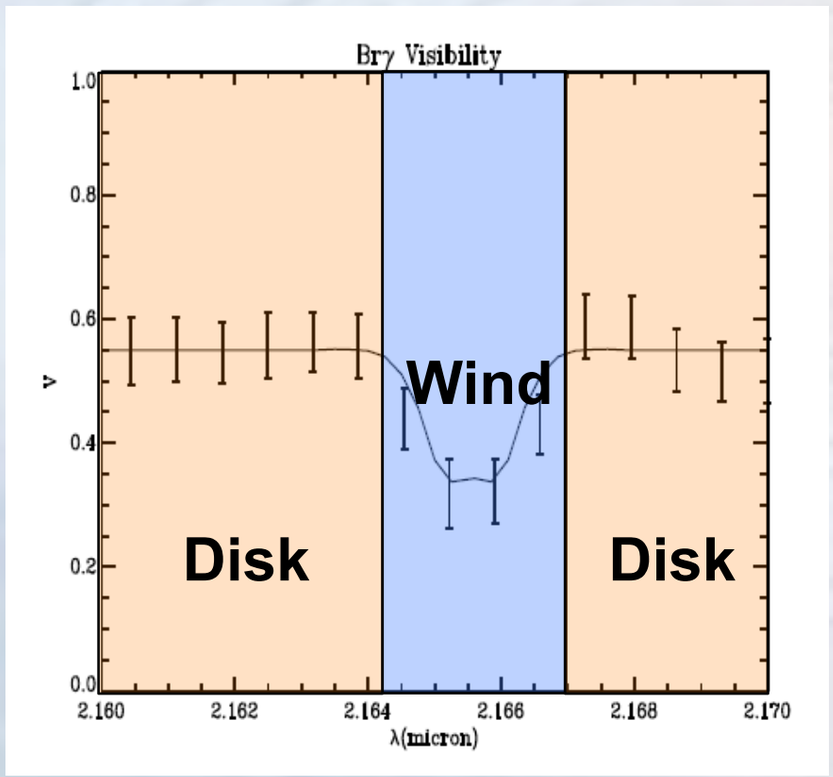
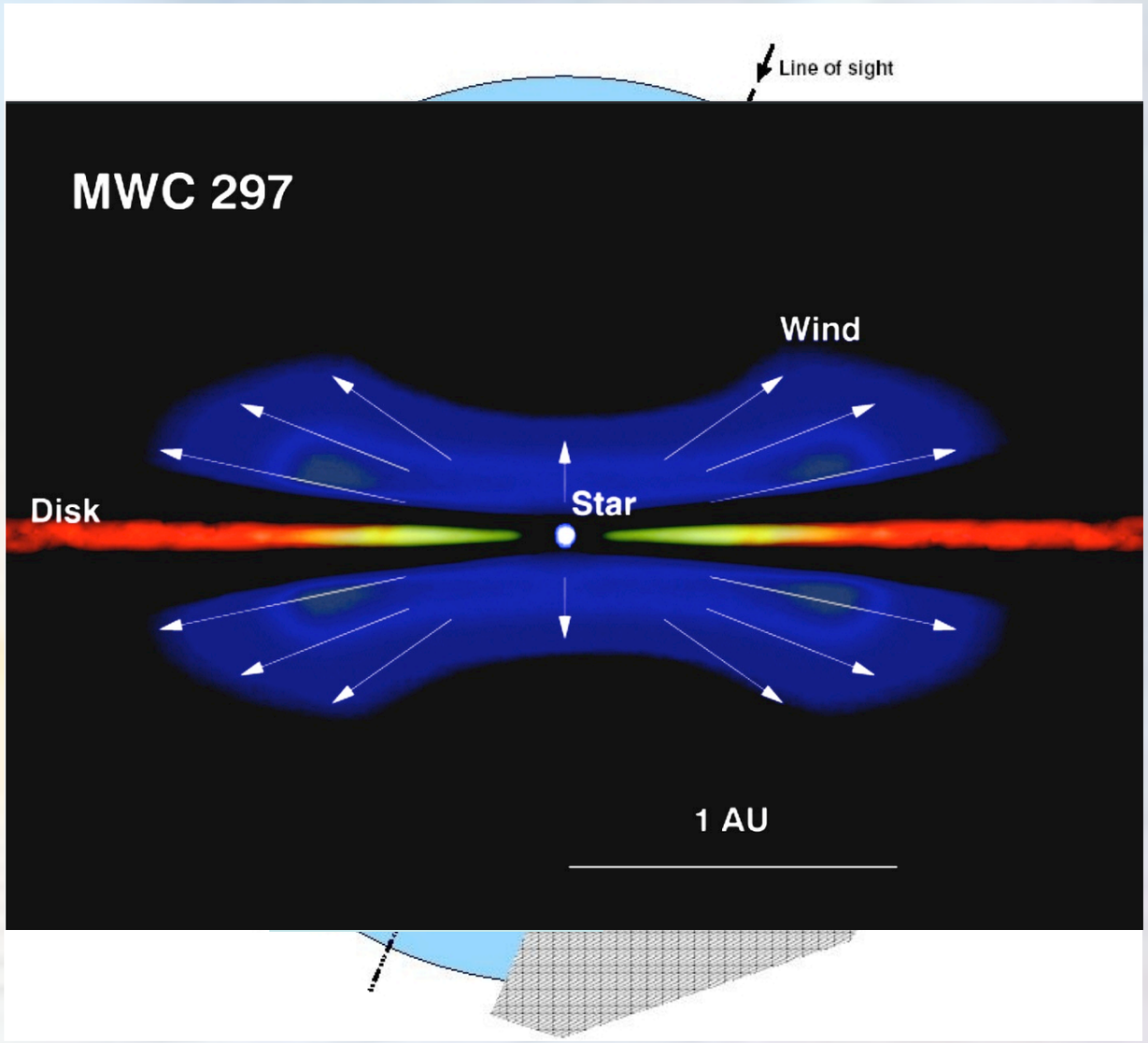




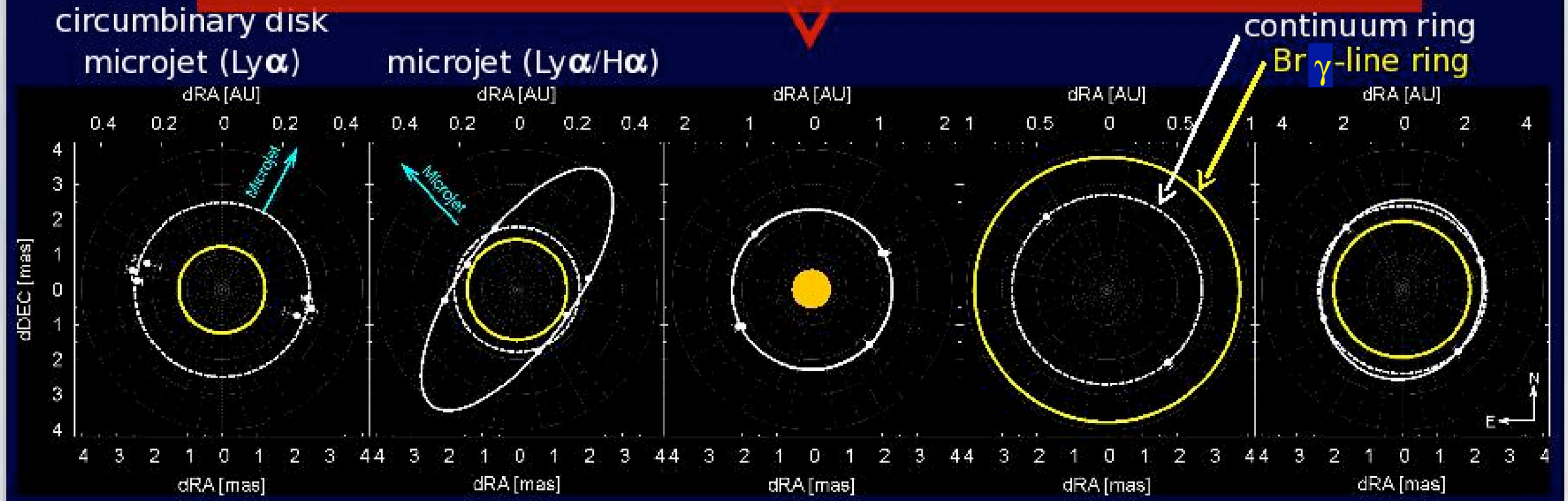


Malbet et al. (2007, A&A 464, 43)

A systematic study of the origin of the BrΥ emission in Herbig Ae/Be stars

very compact Br γ -region (unresolved, $R_{Br\gamma} < 0.2\ R_{cont}$)

→ consistent with magnetospheric accretion

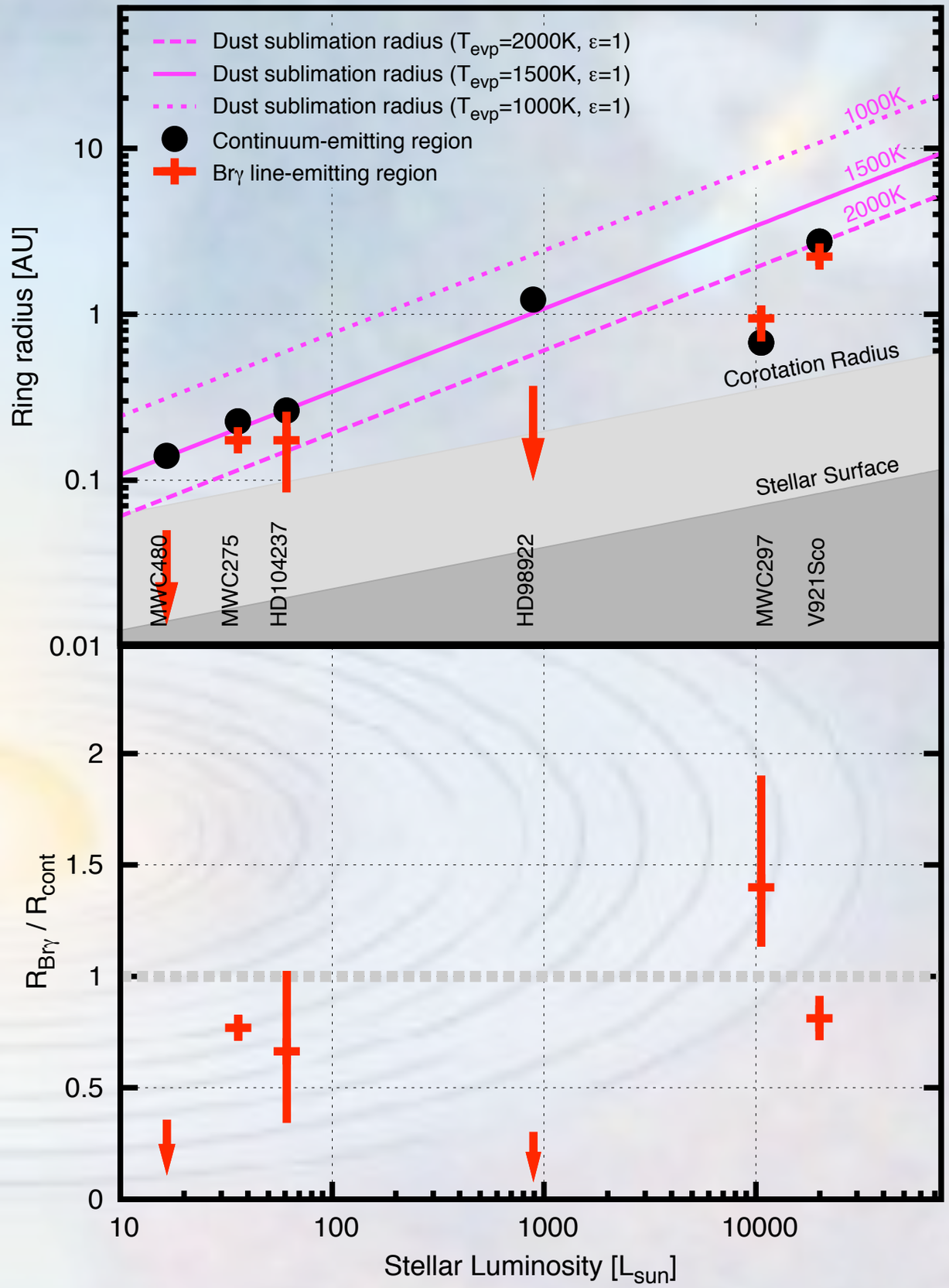


HD 104237 (A5) MWC 275 (A1) HD 98922 (B9) MWC 297 (B1.5) V921 Sco (B0)

extended Br γ -region ($0.6 < R_{Br\gamma}/R_{cont} < 1.4$)

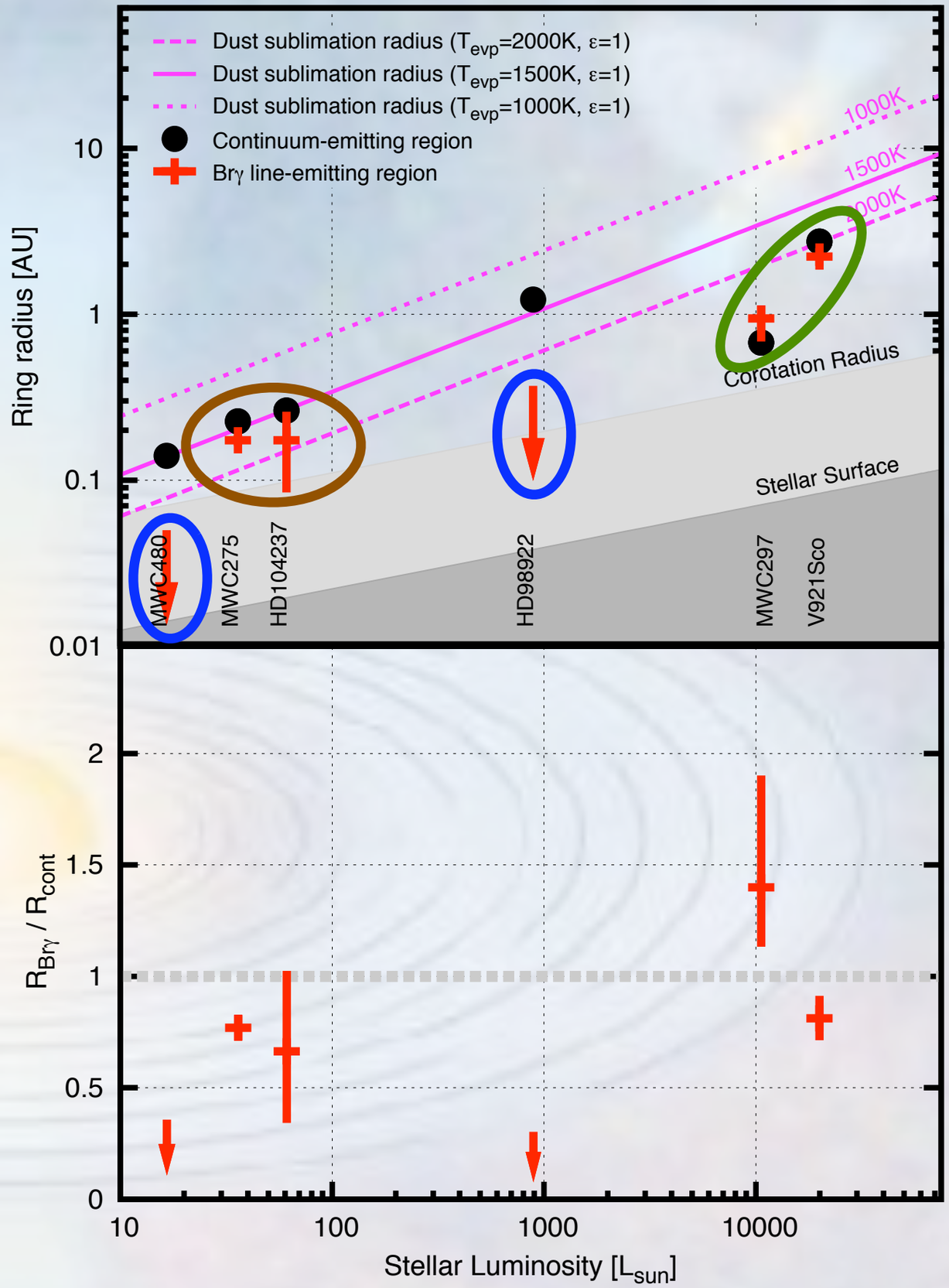
→ consistent with disk wind or stellar wind

Kraus et al. (2008, A&A in press)



Kraus et al. (2008, A&A in press)

- **magnetospheric accretion**
- **disk wind**
- **X-wind or disk wind ?**



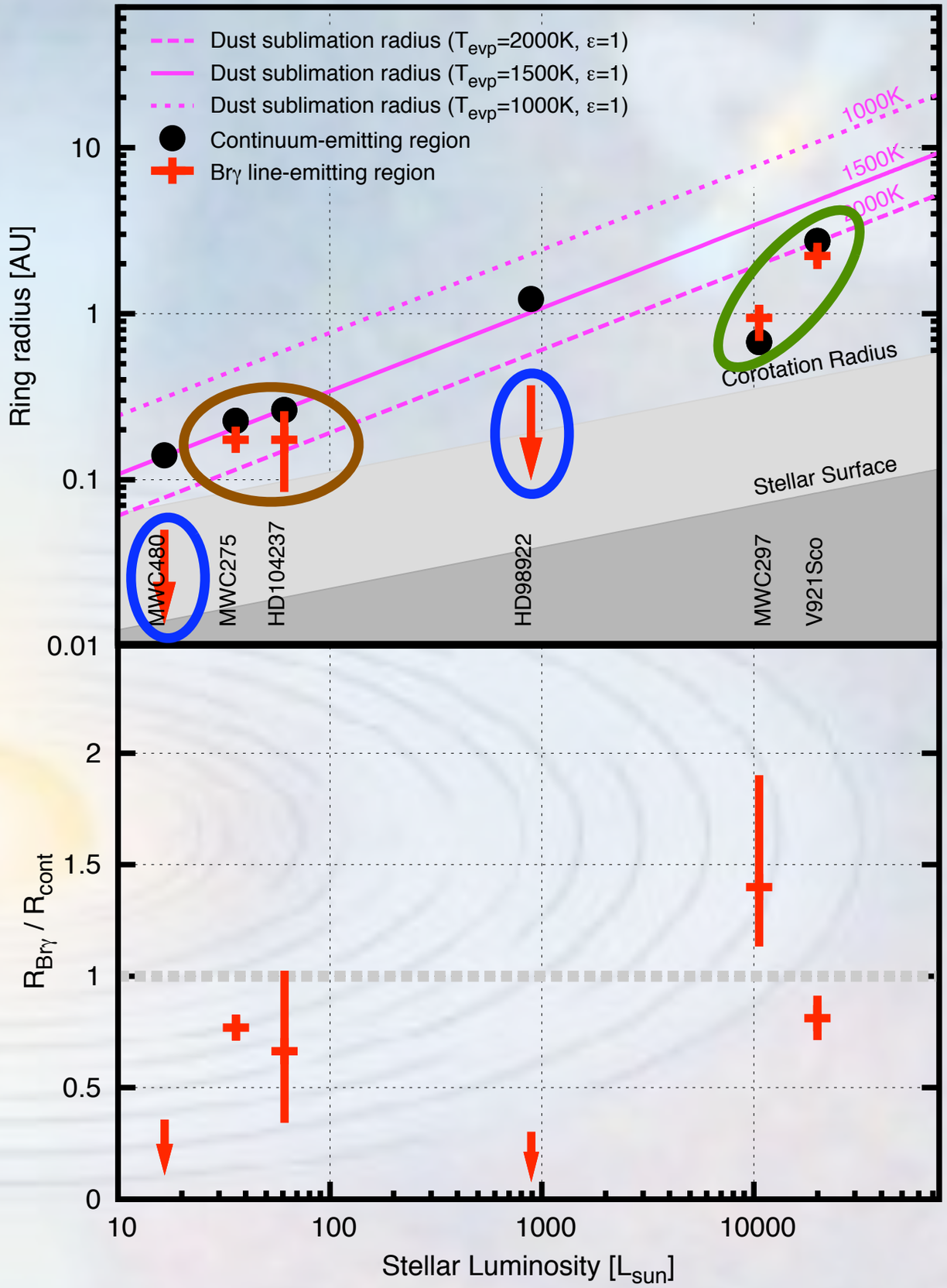
Kraus et al. (2008, A&A in press)

- **magnetospheric accretion**
- **disk wind**
- **X-wind or disk wind ?**

➡ No correlation with L_* as suggested by Eisner et al. 2007

➡ **We are probing mostly outflows phenomena**

➡ Evidence that Brγ is an indirect accretion tracer through accretion-driven mass loss?



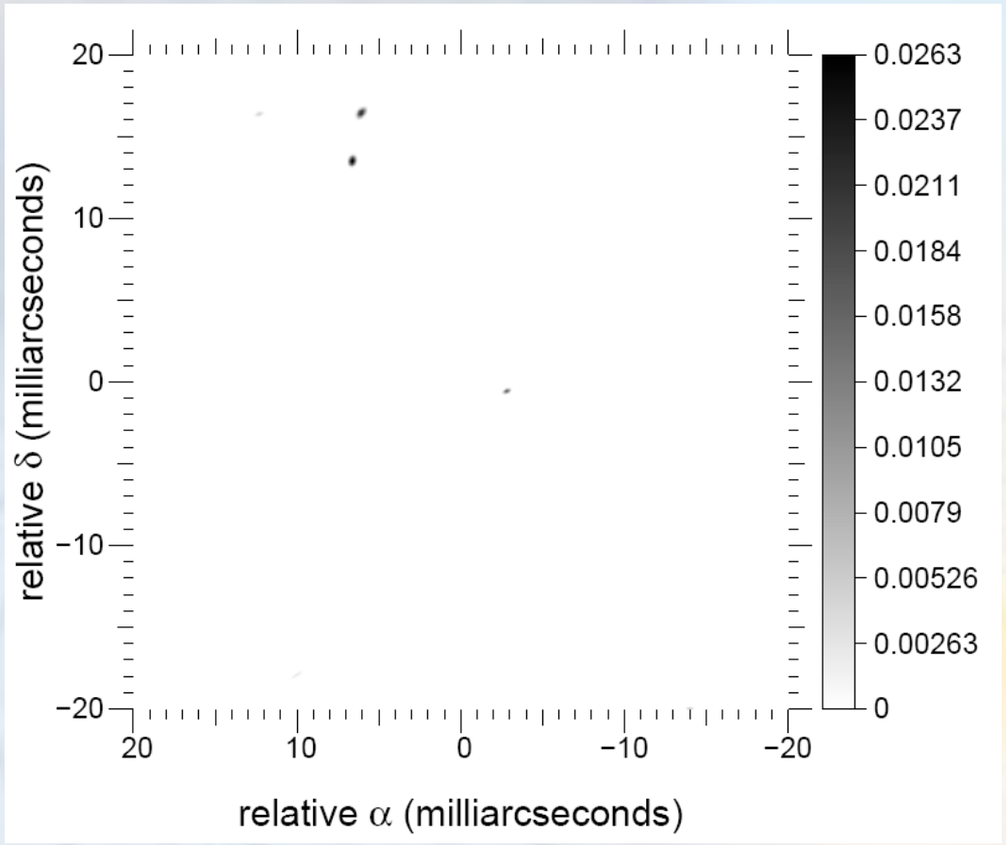
Kraus et al. (2008, A&A in press)

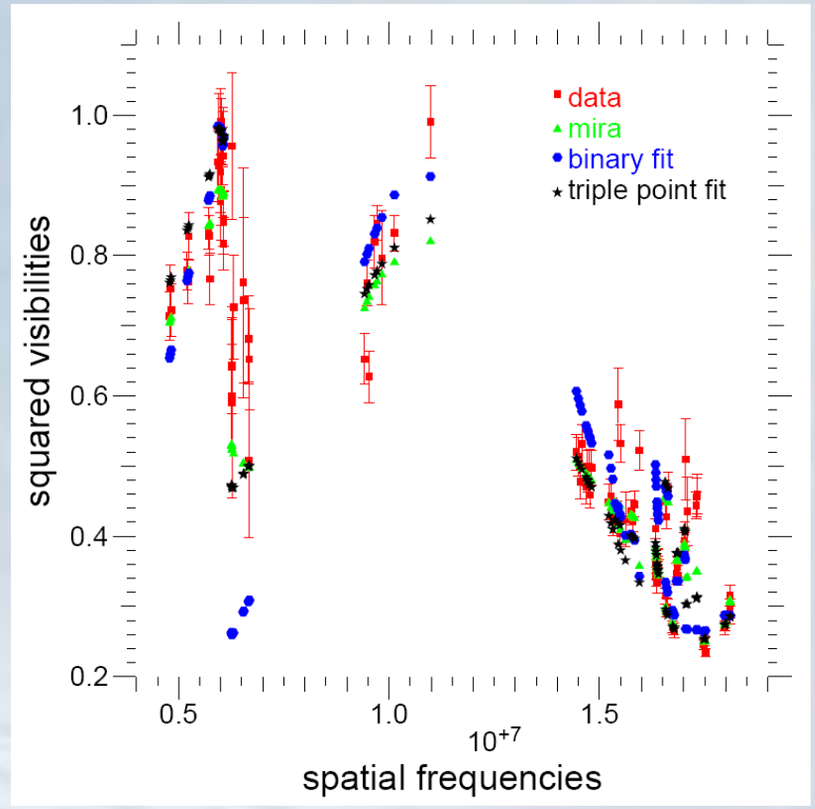
OBSERVATION of EXOPLANETS in DISKS

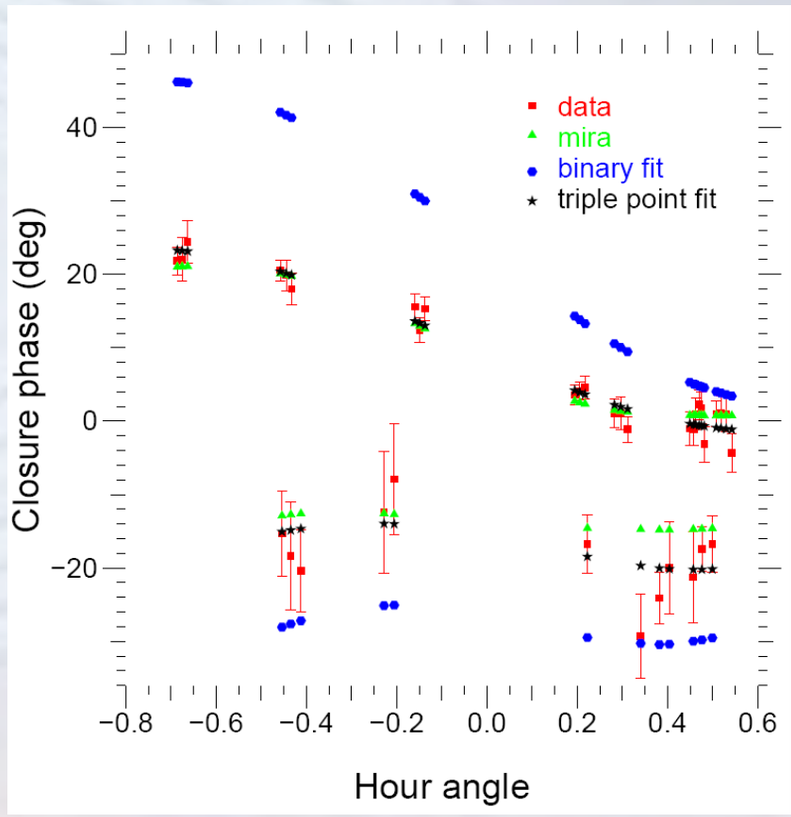
– Multiple systems in YSOs: GW Ori
– Detecting Hot Jupiters with the VLTI
– Detecting planetary gaps in disks

GW Ori: a young SB with an unseen companion

Image reconstruction and triple systemLM fit







Berger et al. (in prep.)

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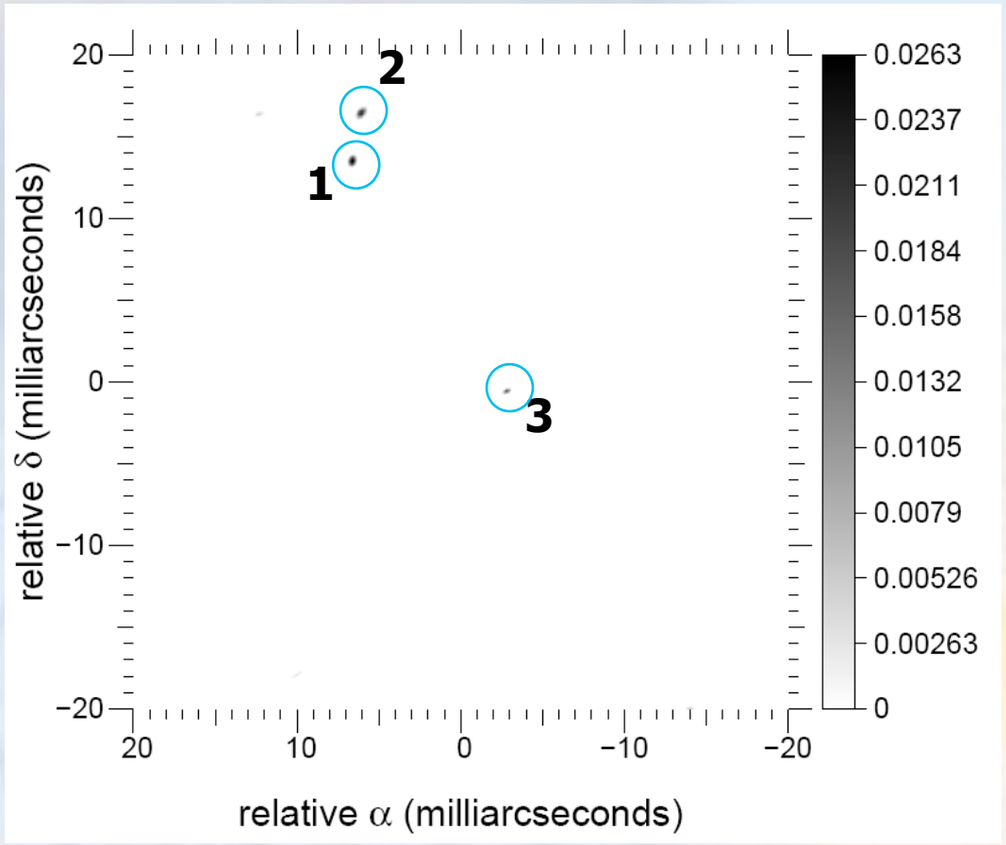

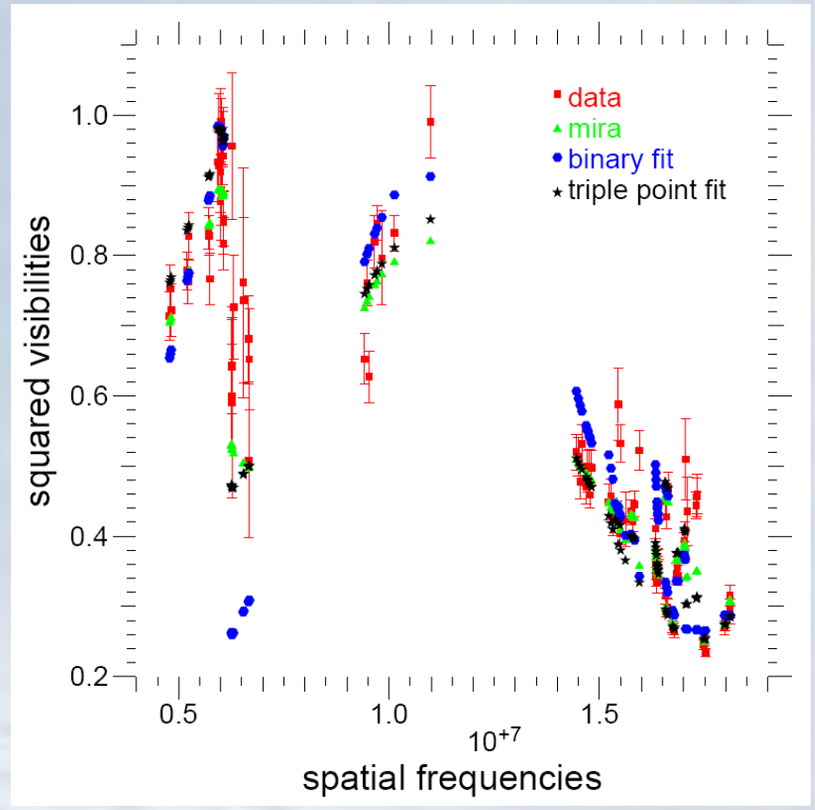

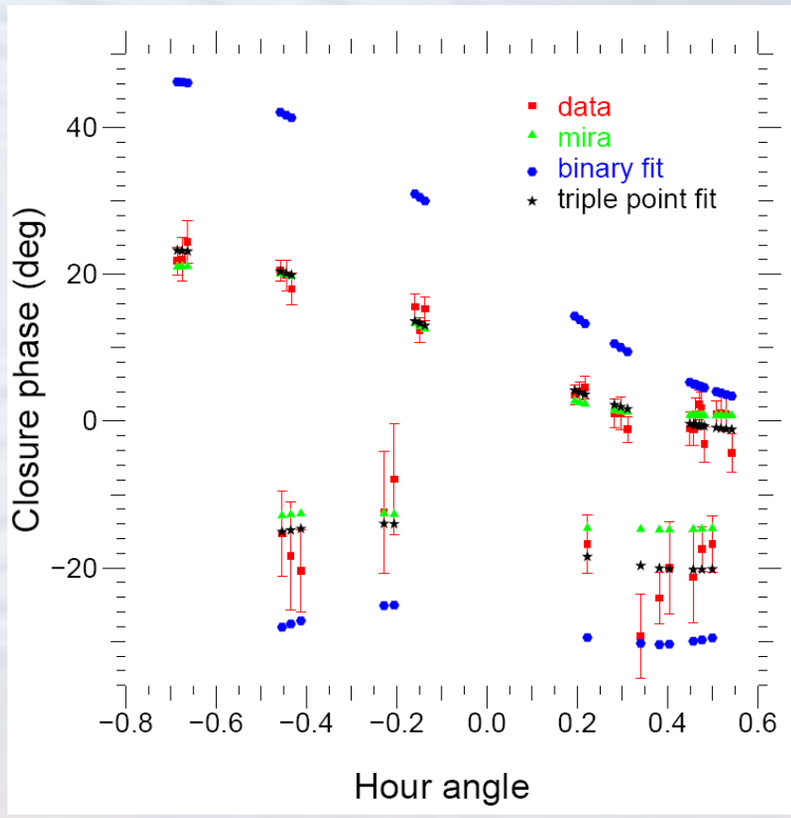

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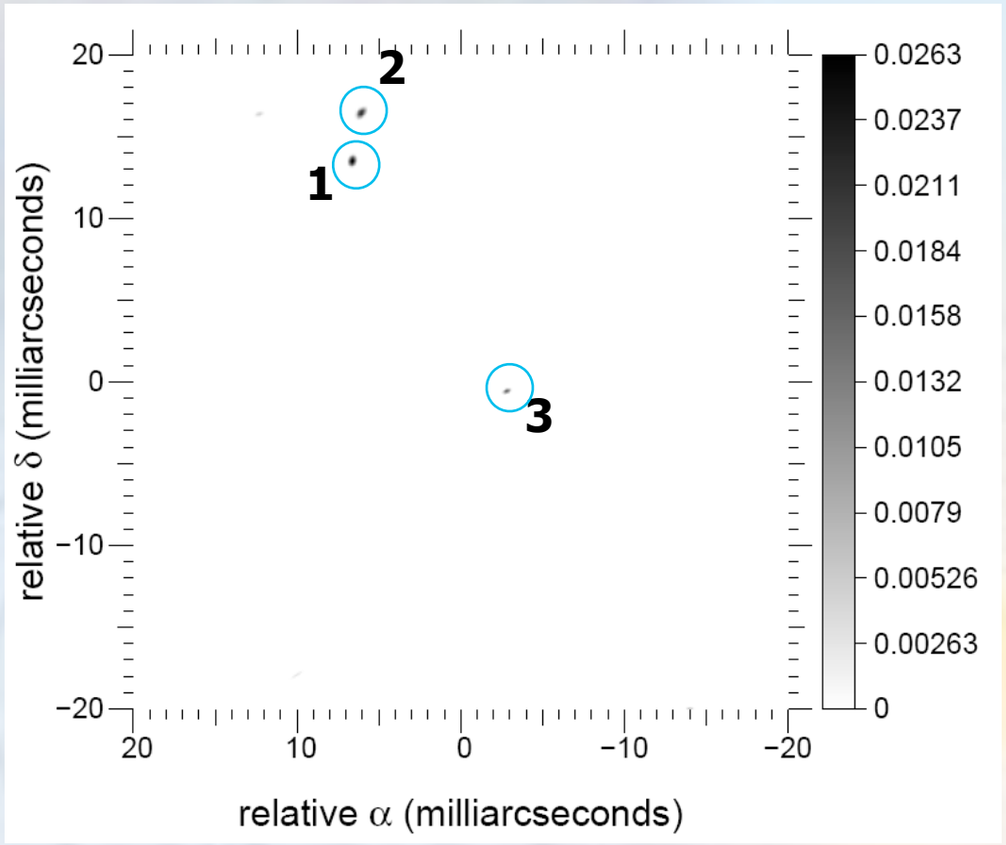
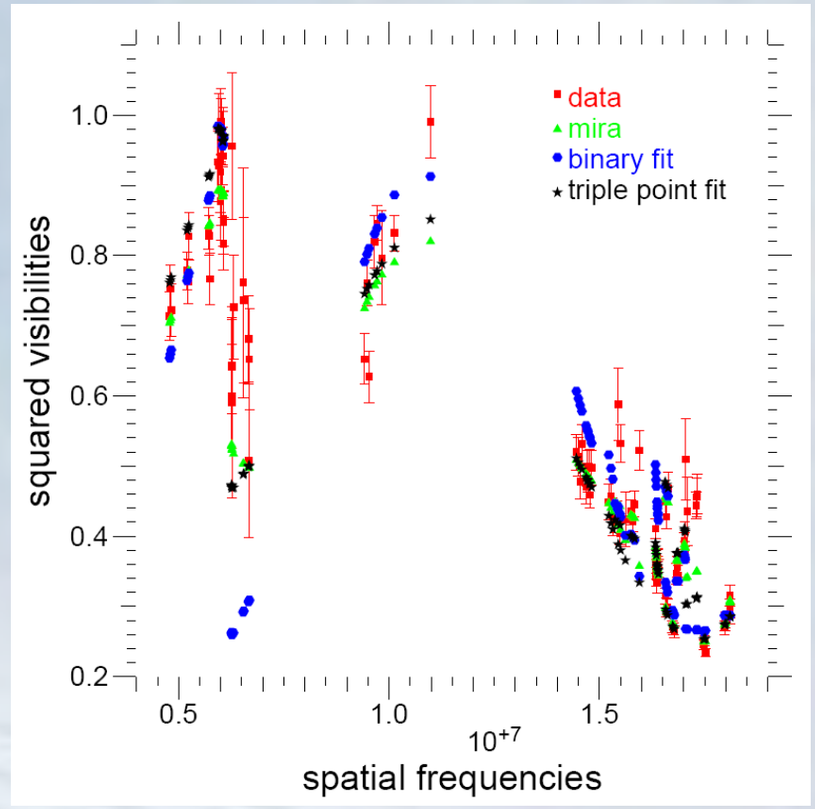
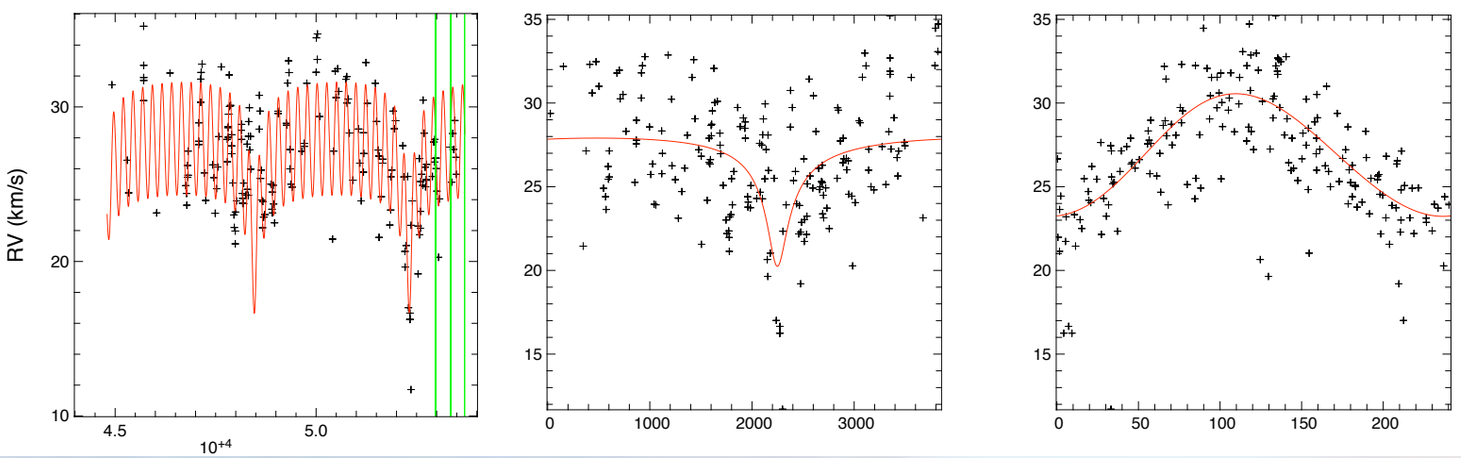
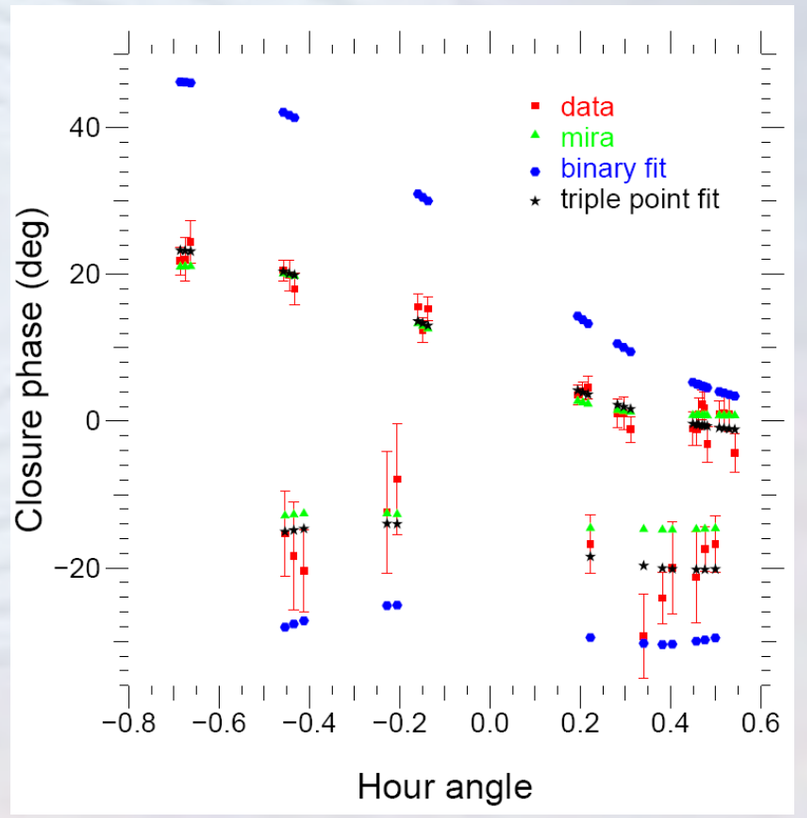




Radial velocities from Latham

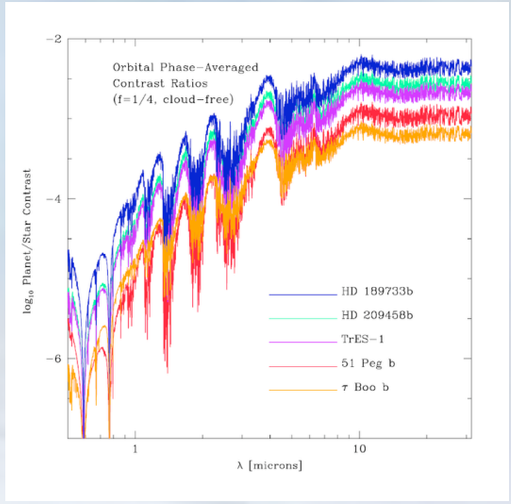




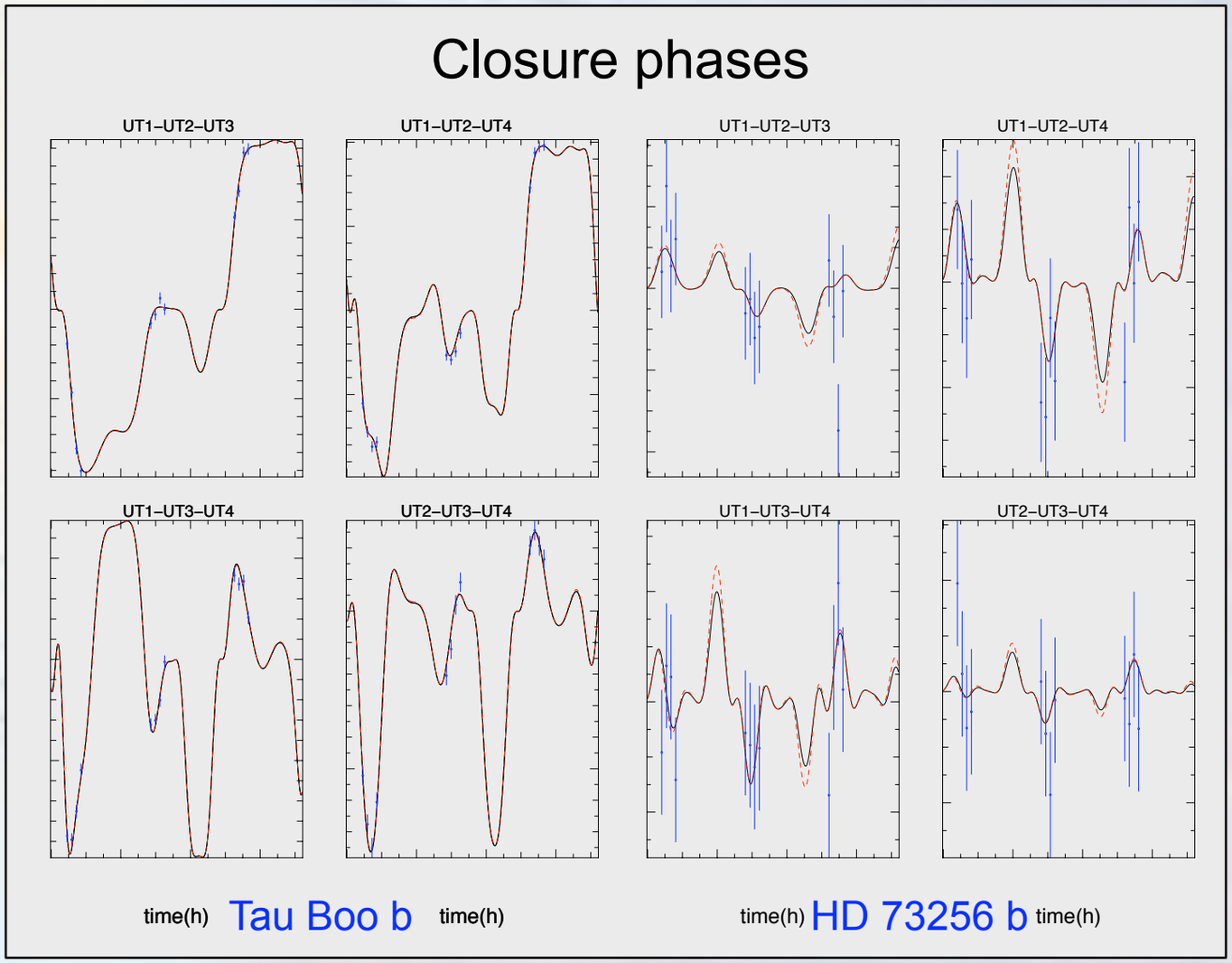
Berger et al. (in prep.)

Detecting hot Jupiters with the VLTI

- Goal: to investigate the potentiality of the VLTI with 4 telescopes (VSI)
- to understand the limits of the phase closure technique
- to be able to propose an actual experiment with present instrument (AMBER)
- 6 favorable cases

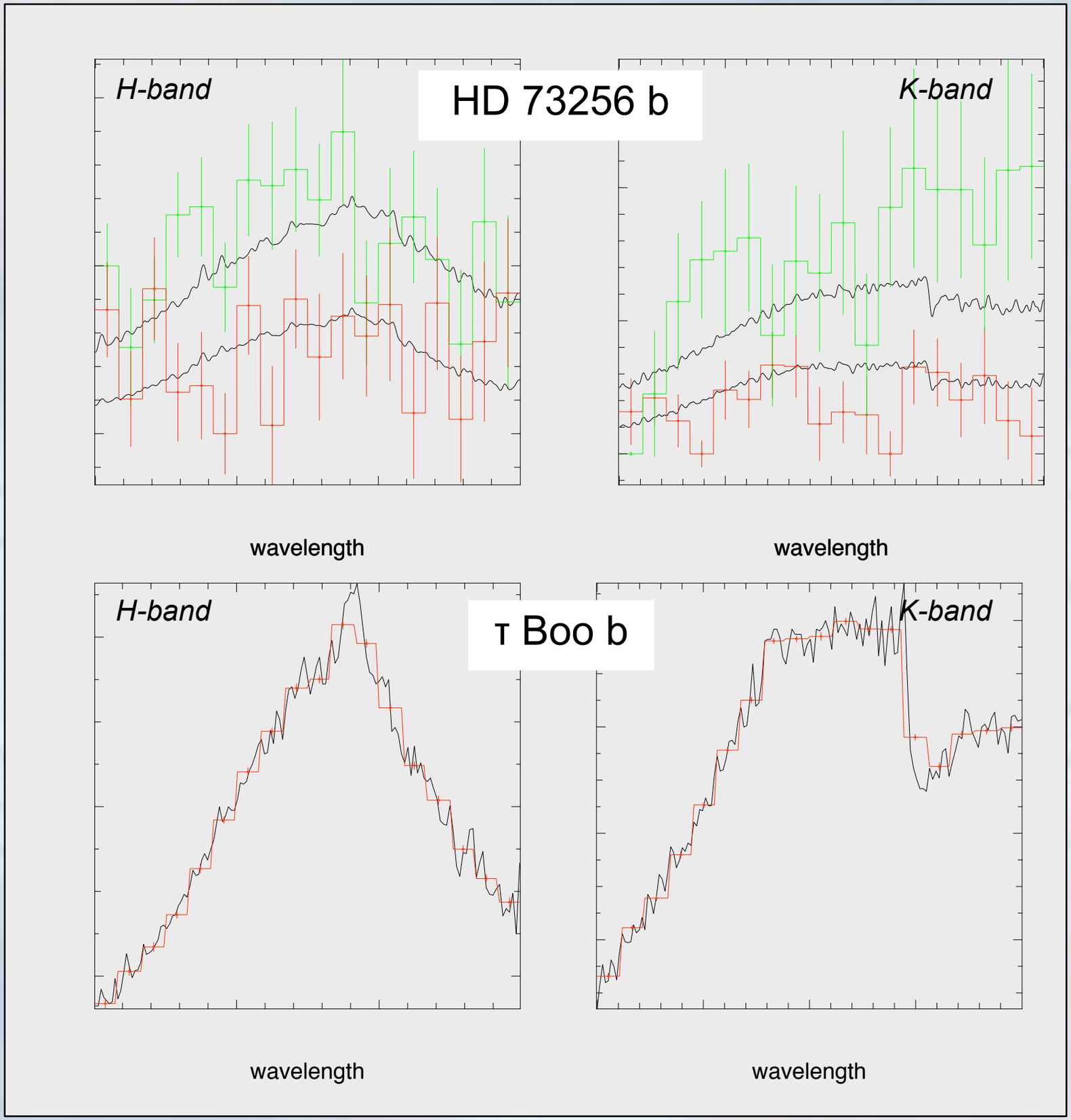


Synthetic spectra from Barman et al. (2001)



Renard, Absil, Berger et al. (SPIE 2008)

... can potentially lead to reconstructed planet spectra



Renard, Absil, Berger et al. (SPIE 2008)

Direct detection of planets: status?

- Run allocated for Jan 2009 to observe with AMBER the star HD 75289

  team: O. Absil, M. Swain, T. Forveille

- The planet detection program is part of the VSI science cases

- Exoplanets around YSOs: to determine the nature of companions around FU Ori and AB Aur

- *New technique*: Phase closure nulling (to be presented soon)

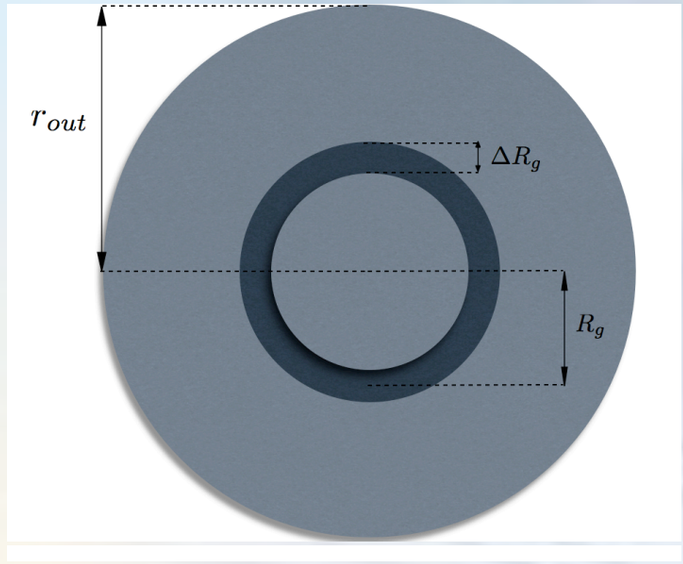
NB: GW Ori astrometry + RV -> similar to the SIM products

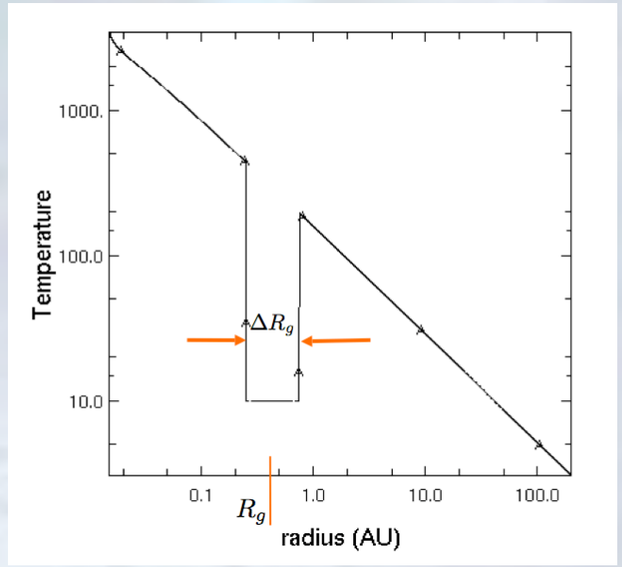
Detecting planet signatures in disks

- Planets do create gaps in protoplanetary disks
- Is an imaging space mission (DARWIN, PEGASE) able to detect gaps at AU scale?
- What is the best way to detect the signatures of gaps?
- Simple analytical model
- Use spectro-interferometry

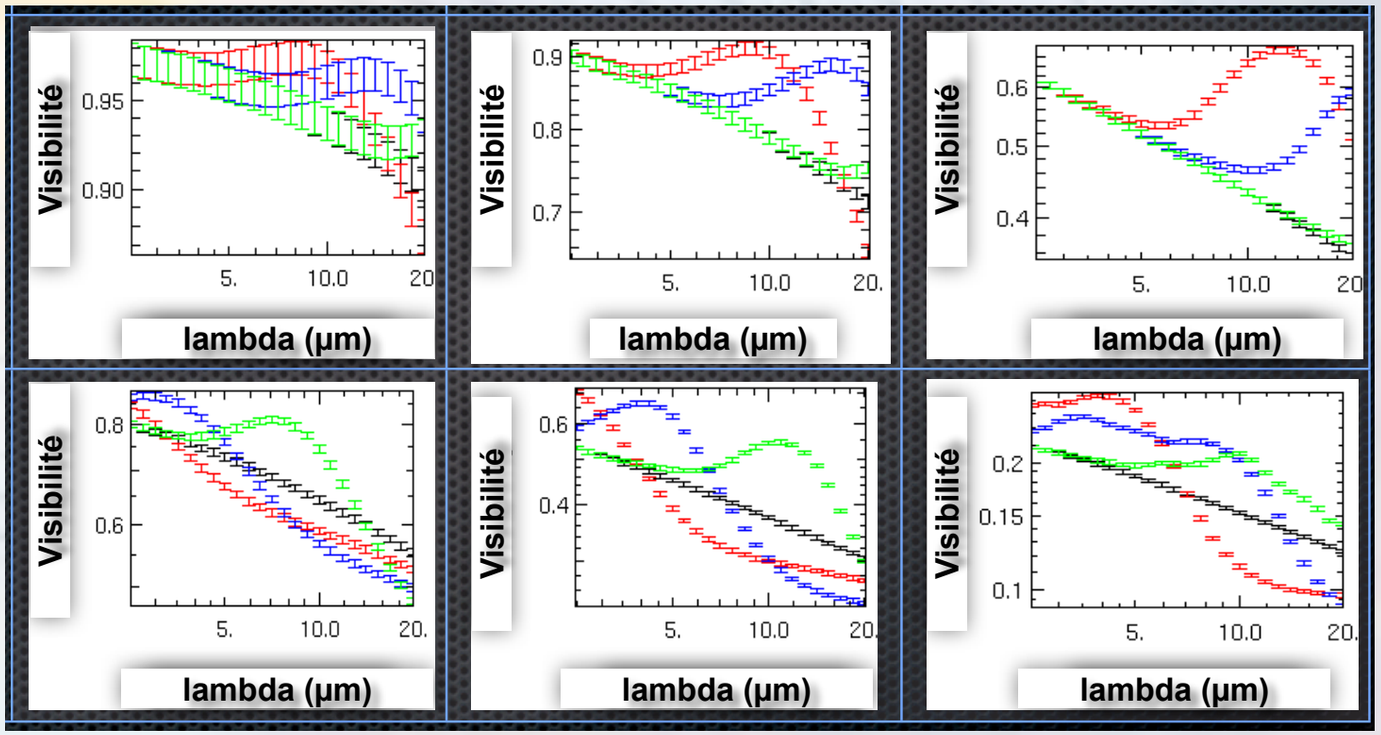
➥ gaps yields to visibility oscillations with λ with

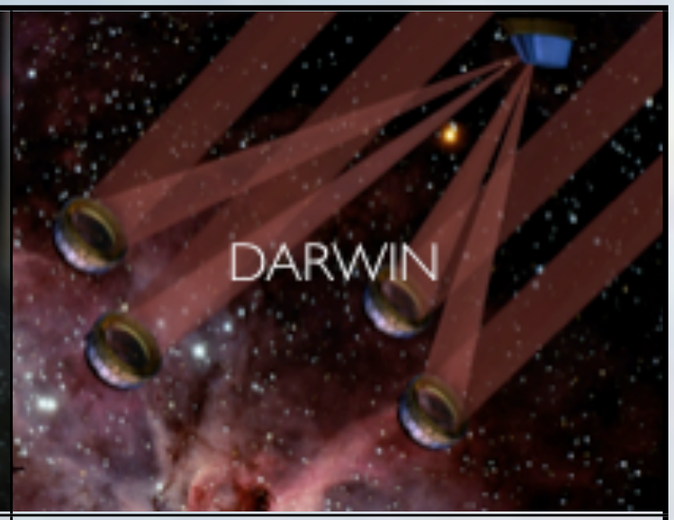
- frequency related to Rg
- amplitude to ΔRg

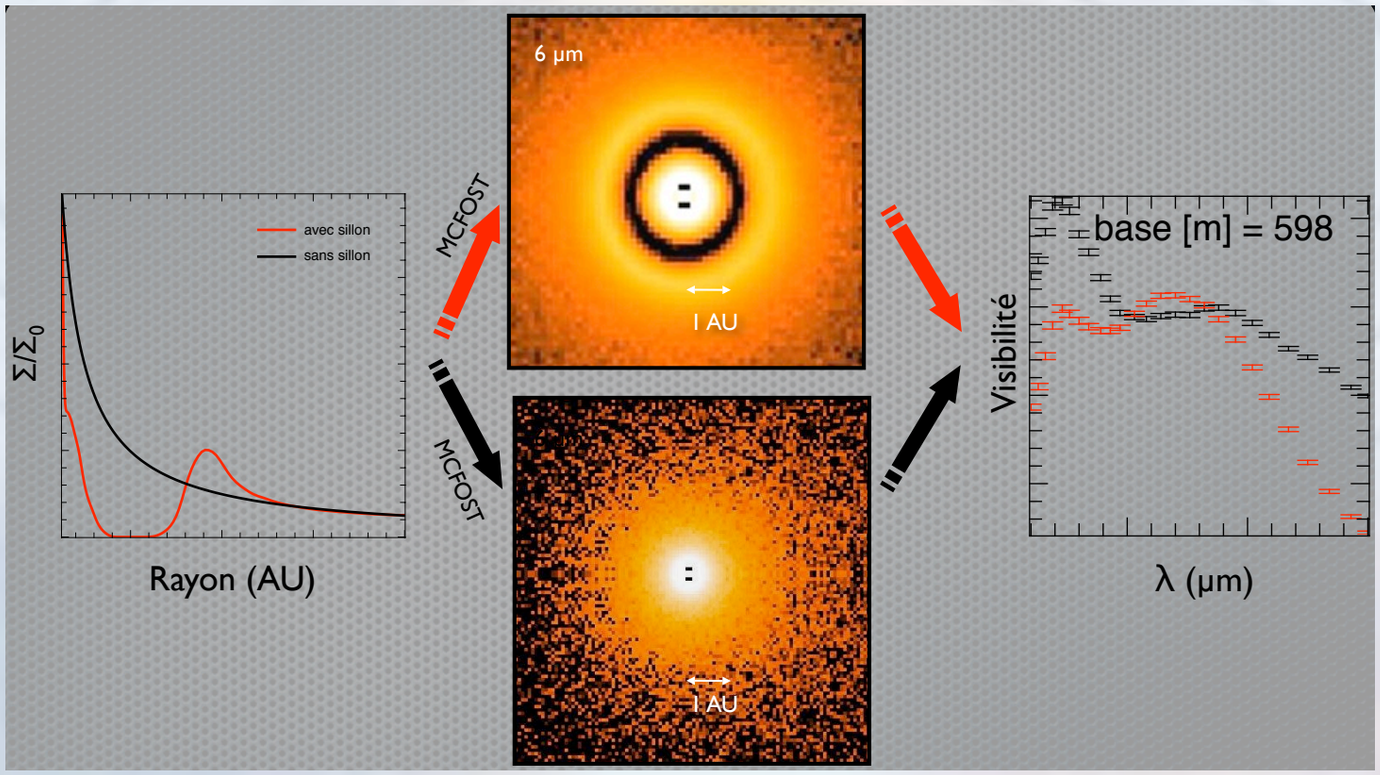




Herwats & Malbet (in prep)



Typical parameters		
Wavelength	1-6µm	6-20µm
Visibilities accuracy	1%	2%
Baseline (m)	200-500 m	200-500 m
Detectability	0.25 → 2 AU	0.5 → 8-12 AU



Herwats & Malbet (in prep)

Validation with SPH simulation in progress....

CONCLUSION

– Summary
– What still to expect from interferometry?
– My projects for the year
– Where to find me?

Conclusion

- Interferometry did a **major leap** in stellar and planet formation in just a decade:
  - 79 objects observed so far,
  - 40 refereed papers
  - new types of observations with **spectral resolution, closure phases, imaging**
- Observations are **mature enough** to allow **detailed modeling**.
- Beginning of **image reconstruction**: input for models

What new to expect in the YSO field with VLTI ?

➥ increased operability of AMBER:

- in practice ~ 15min for one calibrated observation (before ~ 30min)
- AMBER Task Force + optimized data reduction process (new release)

➥ sensitivity: FINITO available with UTs

- increased precision on closure phase (and absolute visibility)
- towards fainter magnitude (T TAuri regime) and surveys
- fainter IR emission lines (CO, Fe?...)
- useful data in J band (Paβ emission)
- very high spectral resolution (R=10000): kinematics/velocity maps

➥ Future VLTI instrumentation: imaging

- 2012: MATISSE: 4-way N-band imaging beam combiner for imaging
- 2012: GRAVITY: 4-way K-band dual-beam recombiner for imaging and very narrow-angle astrometry
- 2015: VSI: 4- and 6-way NIR imaging beam combiner

Both GRAVITY and VSI will use integrated optics (IO) chips as beam combiner

My projects for the year

- **Host**: NExScI/Caltech and JPL/Center for Exoplanet Science
- **Collaborate** with NExScI scientists **on YSOs** (RMG, RA, CBe,...): FU Ori, HAeBes,...
- Discussion about **interferometric imaging** (hardware, fringe tracking, software,...)
- **Exoplanets**: direct detection of hot Jupiters (Swain), planets around young stars, involvement in SIM,...
- Relationship between NExScI and JMMC (software benchmark, tools,...)
- Other area of interests: coronagraphy

Where to find me?

- Tentative weekly schedule:
  - JPL: Mon, Thu
  - IPAC: Tues, Wed, Fri

- No office at JPL yet...

- Office@IPAC: #124 (MR building), Ext.: 1954, Email: <fabien.malbet@caltech.edu>

- Here until end of July 2009